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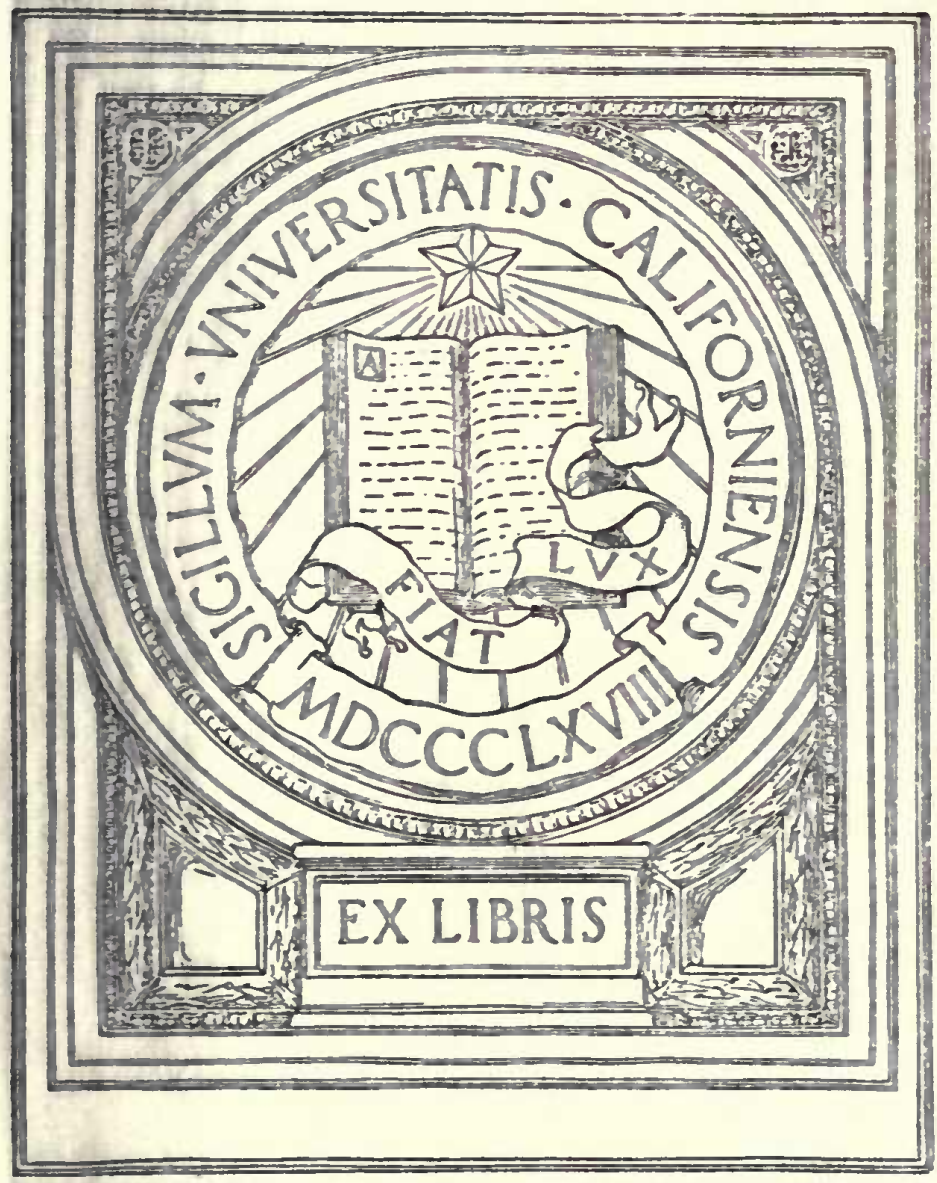

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TRANSMISSION OF POWER

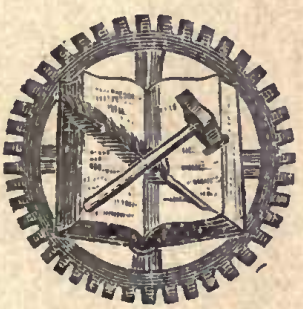
BY

WIRE ROPES.

BY

ALBERT W. STAHL, M. E. '76.
S. I. T.

CADET-ENGINEER U. S. N.



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PREFACE.

It has been my object, in the preparation of this work, to make it a complete exposition of the theory and practice of transmitting power by wire ropes.

No complete treatise on this subject has yet been published in the English language, although the practical part of the matter is well explained by the U. S. Commissioners in their report on the Paris Exposition of 1867, and by an excellent pamphlet written by W. A. Roebling, C. E., to which I am indebted for much practical information.

In Europe, this method of transmitting power has found many ardent supporters. Among them, I may mention Prof. F. Reuleaux of Berlin, who has devoted a number of chapters to it in his various scientific publications, and Messrs. J. J.

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Rieter & Co. of Winterthur, Switzerland. The latter gentlemen have erected by far the greatest number of transmissions there; and their engineer, Mr. D. H. Ziegler, has written quite extensively on the matter.

In this country the John A. Roebling's Sons Co. are the largest manufacturers.

It is to the publications above mentioned, that much of the matter in the following pages is due.

TRANSMISSION OF POWER BY WIRE ROPES.

Section I.

INTRODUCTION.

It is a noteworthy historical fact, that economy in the generation of power in the motor, and economy in its utilization in the machine, have, in most countries, been far in advance of its economical transmission from the one to the other.

Ever since the steam engine became an established fact in the hands of Watt, inventors have been engaged in making improvements to render it still more efficient. The immense strides taken in advance may be well appreciated by even the most casual comparison of the engine of Watt's time, with one of the

powerful and economical engines of the present day.

Not only have such ideas, as the expansion of steam, been developed to a remarkable extent, but even in the smallest details the watchful eye of the mechanic has ever been finding room for improvement.

In the course of invention, the principles upon which the steam engine has been made a practical success have been developed; and during the present century, the chief application of inventive genius has been turned in the direction of improvement in the combination of the parts of the engine itself. There has been no fundamental change in the conception of the necessary parts of the steam engine; but various modifications of the mechanism have been introduced, whereby the power has been economized, or the necessary friction of the parts has been lessened. Influenced by the same spirit which has characterized the scientific advance of this century; by the increasing necessity of more accurate

methods; and forced by the industrial competition of the age to consider the importance of economy of time and energy, the improvers of the steam engine have seen that their inventions would be recognized as valuable, only as they attained the same results with increased simplicity of action, with less waste of power in the working of the mechanism, or with a less supply of fuel.

As the Englishman, Watt, in the last century, found the steam engine an imperfect and wasteful arrangement for utilizing only a small portion of the energy of the steam supplied to it, and by his invention of a separate condenser, and then by his method of making the engine double-acting, made it really a steam engine; so in this century the credit is largely due to Americans, such as Allen, Corliss and others, for improvements by which, in the engines known under their respective names, simplicity of construction, together with perfection of economy in working, have been secured.

While, in the department of steam engineering, as well as in the no less important domain of boiler-making, we are thus devoting all our energies to increasing the efficiency of the prime mover, a painful lack of care is manifest in the utilization of the power which we purchased so dearly. Obtaining only a small fraction of the theoretical power, it becomes us to husband it with the greatest care, and to allow it to do its allotted work with the least possible waste in the transmission from the prime mover to the machine.

Years ago there were excellent water-wheels, and by them were driven machines of surprising ingenuity, but the power was conveyed to the machines by means of cumbersome wooden shafts, upon which were wooden drums for the driving belts; gearing, too, made of wood; slow-moving, awkward contrivances for the purpose, and very wasteful of power. In Oliver Evans' "Millwright's Guide," which is recognized as the standard book of his time, we read

of wooden shafts, wooden drums, and wooden gearing only.

At a later day, gear wheels were used to transmit the power from the motor to the shaft, while belts or bands were only used to transmit the power from the shafts to the individual machines.

The transmission of power to distances was accomplished by lines of shafting, either laid in ditches underground, or supported on columns high enough not to impede passage beneath the shafts. But even this method was seldom used, except in cases of necessity, owing to its immense first cost.

Although among the most efficient means of transmitting power to short distances, both belting and shafting have the disadvantage, that when the distance becomes great, the intermediate mechanism absorbs an important portion of the power by vibrations, friction, and resistances of every nature; and, for a distance of several hundred feet, we do not get, at one end of the transmission, more than an extremely small fraction of the power applied to the other.

In the case of a mere dead pull, as in working a pump, work is, and has long been, transmitted to great distances; as by the long lines of "draw-rods," used in mining regions to transmit the power of a water-wheel by means of a crank on its main axis, pulling, during half its revolution, against a heavy weight, and thus storing up energy for the return stroke, as the rods, on account of their flexibility, cannot be used to exert a pushing strain. Rotary motion, however, cannot be economically produced in this manner.

Another method, which has been much employed recently, is that known as hydraulic connection; and Armstrong has even perfected apparatus by which water pressure, thus transmitted through, perhaps, miles of pipe, may be converted into rotary motion.

Compressed air has also come largely into use, and there is no doubt that power may be transmitted to great distances by rarefied or compressed air, and may be converted into rotary motion at

any desired point. But in the compression of air, heat is generated; and the latter being conducted rapidly away by the sides of the tube, the loss from this source alone becomes very serious. Another disadvantage, incident on both of the last two cases, is that unless the area of the tubes is very large compared with the current flowing through them, the loss by friction rises to a large percentage of the power transmitted. The capital to be sunk in pipes, therefore, is very large, and both this expenditure and the waste of power increase directly with the distance.

Such were some of the methods employed to transmit power to great distances, before the invention of transmission of power by wire ropes by the Brothers Hirn, of Mulhausen, Switzerland.* These gentlemen have stated the question of the transmission of power in the most general manner, *i. e.*, independently of the intensity of the pressure to be

* See "Notice sur la transmission telodynamique, par C. F. Hirn (Colmar, 1862)."

transmitted, and of the distance to be passed over; and the solution which they have given to this grand problem is so simple, that the apparatus proposed seems, to the casual observer, to be little else than a more extended application of that commonplace "wrapping connector," the belt and pulley. The principle involved, however, is something entirely different.

Simplicity, always the fundamental characteristic of great inventions, rarely shows itself more clearly than in, as they are called, the telodynamic cables. To a person seeing them in operation, they seem the embodiment of simplicity; nevertheless, the Brothers Hirn have the undisputed honor of inventing them. To satisfy themselves on this point, the International Jury at the Paris Exposition in 1867 made a deep research, and examined the patent registers for many years back, but failed to find anything bearing the least resemblance to the telodynamic cables.

This method of transmitting power depends upon two principles in mechanics:

(1) The dynamic force is measured by the product of the force and the velocity with which it moves;

(2) In mechanical work, power may be exchanged for velocity, and velocity for power.

To illustrate, let us suppose a bar of iron, having a cross sectional area of one square inch, to move endlong at the rate of two feet per second. Now, if the resistance overcome is say 5,000 pounds, work will be performed at the rate of 10,000 foot-pounds per second. Now, if we double the velocity of the bar, we will transmit twice the amount of work with the same strain, or the same work may be produced with only half the former strain, *i.e.*, by a bar having an area of only half a square inch. In a similar manner, if we move the bar with the velocity employed in telodynamic transmission, viz., about eighty feet per second, then, while doing the same amount of work, the strain on the bar will be reduced from 5000 to 125 pounds, and the bar will only need a section of 1-40 square inch. To

put an extreme illustration, we might conceive of a speed at which an iron wire, as fine as a human hair, would be able to transmit the same amount of work as the original one-inch bar.

By the application of these simple principles in Hirn's apparatus, the greater part of the force is first converted into velocity, and at the place where the power is required, the velocity is changed back into force.

Section II.

THE DRIVING WHEELS.

The construction of the apparatus is very simple. A tolerably large iron wheel, having a V shaped groove in its rim, is connected with the motor, and driven with a perimetral velocity of from sixty to one hundred feet.

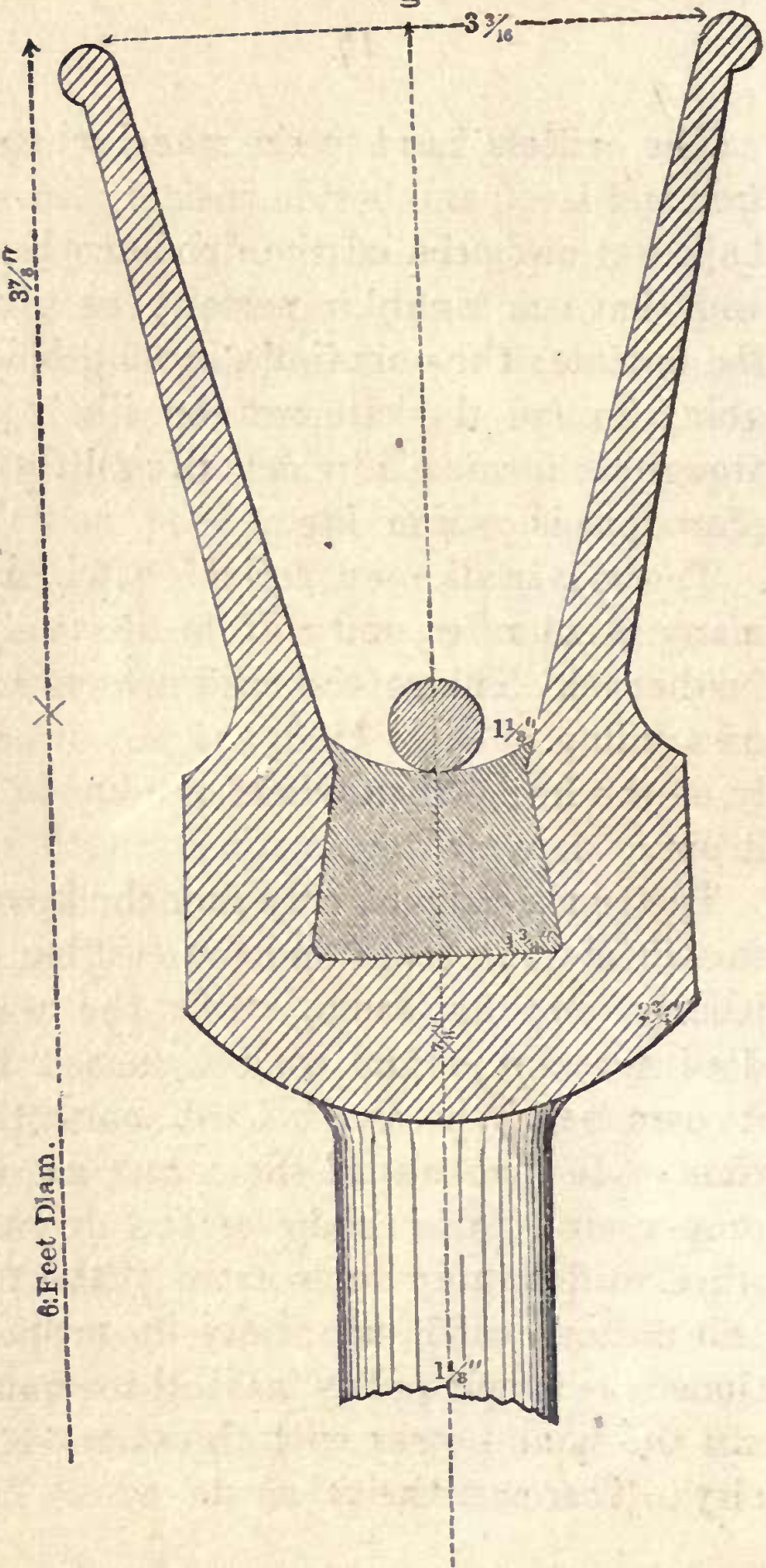
Round this wheel is passed a thin wire rope, which is led away to almost any reasonable distance (the limit being measurable by miles), where it passes over a similar wheel, and then returns

as an endless band to the wheel whence it started.

The peripheries of the driving wheels may have an angular velocity as great as possible; the only limit, in fact, being that the speed shall not be likely to destroy the wheels by centrifugal force. The speeds which have been actually employed in the examples to which I propose to refer, vary from 25 to 100 feet per second, at the circumference of the pulley.

The wheels themselves are made as light as is consistent with strength, not only for the sake of reducing the inertia of the moving mass, and the friction on the axis to a minimum, but for the equally important object of diminishing the resistance of the air. It can hardly be doubted that abandoning spokes entirely, and making the pulley a plain disc, would improve essentially the performance, could such discs be made at once strong enough to fulfill the required function, and light enough not materially to increase the friction.

Fig. 1



The wheels have been made of cast iron and steel, and beside their lightness, have but one peculiarity of construction, and that is a highly important one. At the bottom of the acute V shaped groove, going around the circumference, a little trough is formed in which the filling is placed, as shown in Fig. 1.

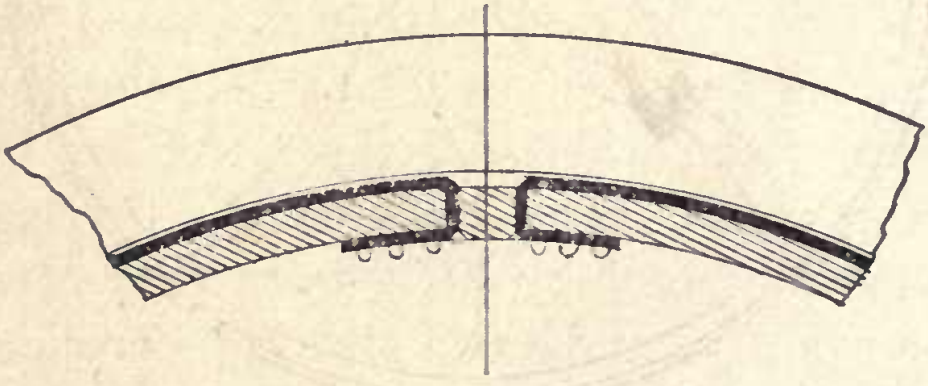
The materials used for this filling are many in number, and will be discussed further on. The rope should always run on a filling of some kind, and not directly on the iron, which would quickly wear it out.

The rope is not tightly stretched over the wheels, but, to all appearances, hangs loosely on the same. But the rope does not slip, as the tension caused by its own weight presses it hard againt the rims of the wheels, if the latter are of proper size. The body of the driving wheel differs very little from that of a belt pulley; and it can always be proportioned as a belt pulley having to transmit the same power with the same velocity. The peculiarity of the wheel lies

Fig. 2

in its rim, as previously explained. In the early experiments on the transmission of power in this manner, the rims were made of wood with a leather belt as filling, (see Figs. 2 and 3).

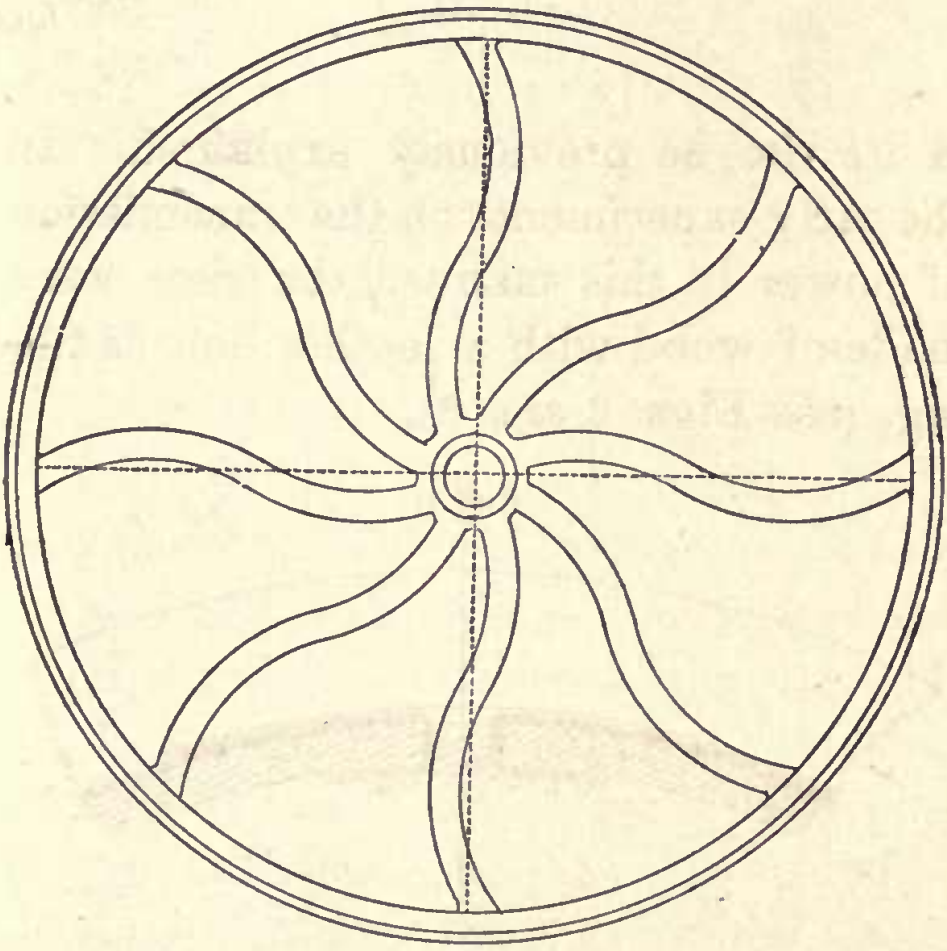
Fig. 3



This kind of rim has now gone entirely out of use, and has been replaced by a

wheel cast solid with an iron rim, whose edges, in a a single grooved wheel, are inclined at about twenty-five degrees from the vertical, (Figs. 1 and 4). In some instances where the ropes were exposed to a high side wind, the slope has been made as great as 45°, but this a very unusual case.

Fig.4



The angle of 30°, if used in a double grooved wheel, would give an extremely

heavy central rib, on which account the sides of the latter are usually made steeper, viz., about 15° from the vertical. Wheels from about nine feet in diameter up are usually cast in halves and afterward fastened together on the shaft. In order that the centrifugal force may not become dangerous, the perimetral velocity should not exceed 90 to 100 feet per second. Velocities up to 90 feet have been frequently used, without any prejudicial results whatever.

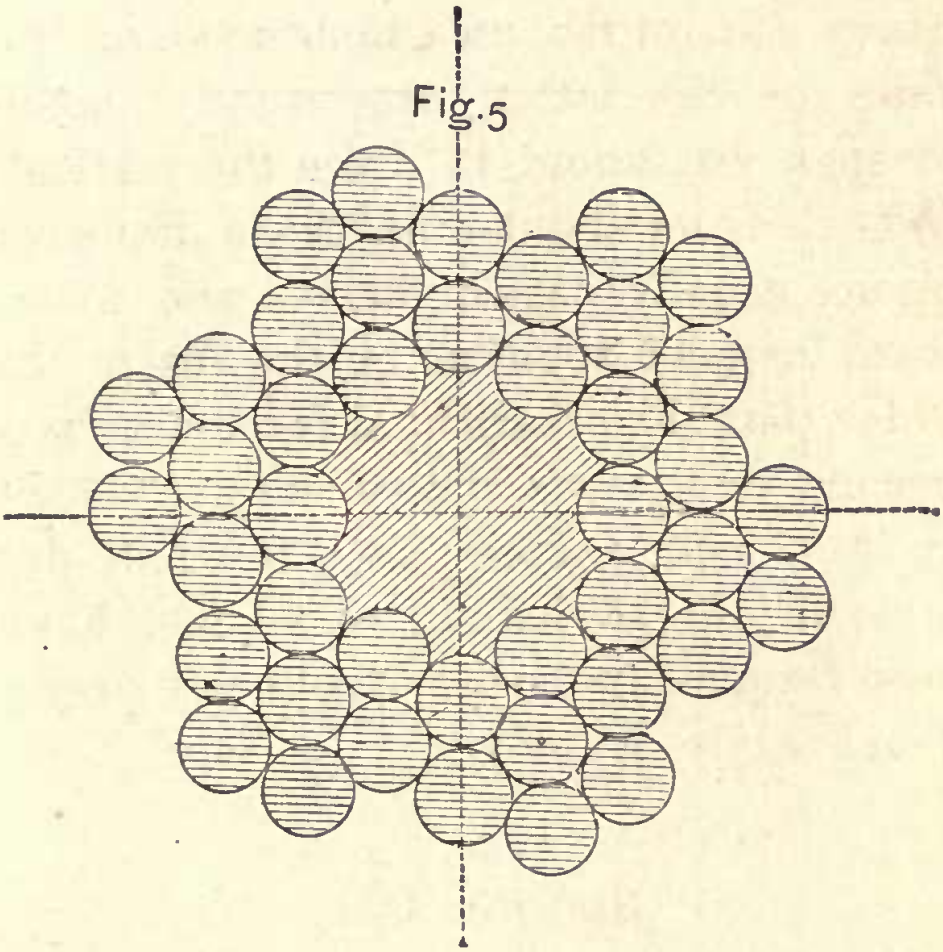
Section III.

THE DRIVING ROPES.

The driving rope usually employed in this country consists of six strands, with seven wires to each strand (see Fig. 5). The strands are spun around a hempen center or core, thus obtaining the necessary flexibility.

When wire rope is referred to in this thesis without special qualification, it is to be understood to mean Messrs. J. A. Roebling's Sons' 42 wired round iron

Fig. 5



wire rope. The diameter of this kind of rope is nine times the diameter of the wire of which it is composed. That is to say, if D = the diameter of the rope, and d = diameter of the wire, then D = $9d$.

The following table gives the weight, strength, etc., of Messrs. Roebling's

42 WIRED ROPE :

Trade Number.	Diameter in inches.	Circumference in inches.	Weight per foot in pounds.	Ultimatestrength in pounds.	Proper tension in pounds.	Price per foot in cents.
25	$\frac{1}{4}$	$\frac{7}{8}$	.125	2060	515	5
24	$\frac{9}{32}$	1	.162	2760	690	7
23	$\frac{5}{16}$	$1\frac{1}{8}$	.189	3300	825	8
22	$\frac{3}{8}$	$1\frac{1}{4}$	.23	4260	1065	9
21	$\frac{7}{16}$	$1\frac{3}{8}$	.3	5660	1415	10
20	$\frac{1}{2}$	$1\frac{5}{8}$	.41	8200	2050	12
19	$\frac{5}{8}$	$1\frac{7}{8}$	.5	11600	2900	14
18	$\frac{11}{16}$	$2\frac{1}{8}$	.686	15200	3800	17
17	$\frac{3}{4}$	$2\frac{3}{8}$	.86	17600	4400	20
16	$\frac{7}{8}$	$2\frac{5}{8}$	1.12	24600	6150	25
15	1	3	1.43	32000	8000	32

In the manafacture of the rope, the quality of the iron wire must be inspected very carefully, in order to insure durability. The best wire is that made of Swedish iron, uniting great toughness with great tensile strength. Steel wire has not been found well adapted for this work. Particular attention must be paid to getting each wire as long as possible, so as to lessen the number of joints.

In splicing a wire rope, the greatest care must be taken to leave no projecting ends or thick parts in the rope. On this subject, I can do no better than give Messrs. Roebling's directions for making a long splice in an endless running rope of half inch diameter.*

Tools required: One pair of nippers, for cutting off ends of strands; a pair of pliers, to pull through and straighten ends of strands; a point, to open strands; a knife, for cutting the core; and two rope nippers, with sticks to untwist the rope; also a wooden mallet.

First.—Heave the two ends taut, with block and fall, until they overlap each other about twenty feet. Next, open the strands of both ends of the rope for a distance of ten feet each; cut off both hemp cores as closely as possible (see Fig. 6), and then bring the open bunches of strands face to face, so that the opposite strands interlock regularly with each other.

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* See "Transmission of Power by Wire Ropes," by W. A. Roebling, C. E.

Secondly.—Unlay any strand, *a*, and follow up with the strand 1 of the other end, laying it tightly into the open groove left upon unwinding *a*, and making the twist of the strand agree exactly with the lay of the open groove, until all but about six inches of 1 are laid in, and *a* has become twenty feet long. Next cut off *a* within six inches of the rope (see Fig. 7), leaving two short ends, which must be tied temporarily.

Thirdly.—Unlay a strand, 4, of the opposite end, and follow up with the strand, *f*, laying it into the open groove, as before, and treating it precisely as in the first case (see Fig. 8). Next, pursue the same course with *b* and 2, stopping, however, within four feet of the first set; next with *e* and 5; also with *c*, 3 and *d*, 4. We now have the strands all laid into each other's places, with the respective ends passing each other at points four feet apart, as shown in Fig. 9.

Fourthly.—These ends must now be secured and disposed of, without increasing the diameter of the rope, in the fol-

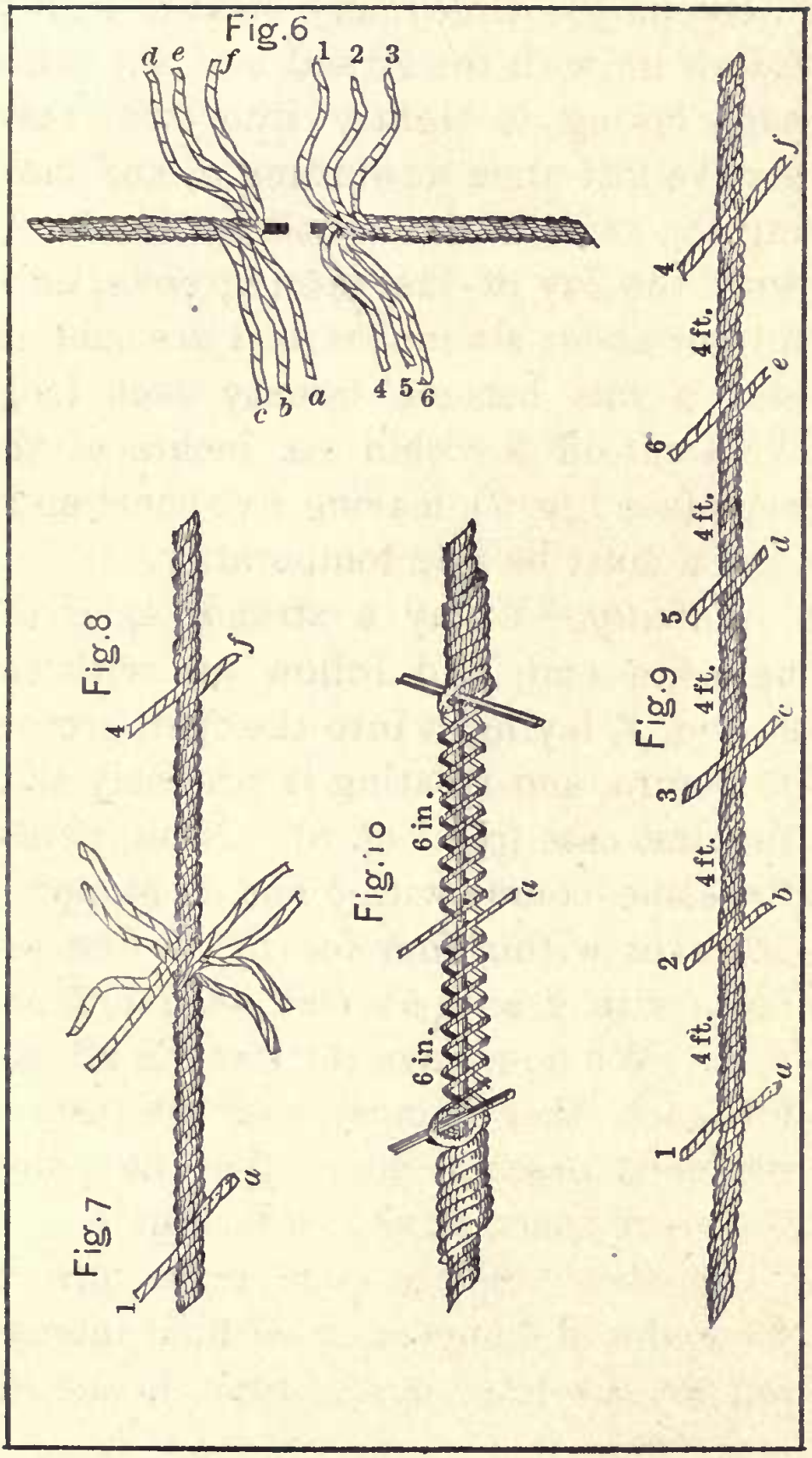


Fig.6
d e f
1 2 3
c b a
4 5 6
Fig.7
1
a
Fig.8
4
f
Fig.10
6 in.
6 in.
a
Fig.9
1
a
4 ft.
2
b
4 ft.
3
c
4 ft.
5
d
4 ft.
6
e
4 ft.
4
f

lowing manner: Nipper two rope-slings around the wire rope, say six inches on each side of the crossing point of two strands. Insert a stick through the loop and twist them in opposite directions, thus opening the lay of the rope (see Fig. 10). Now cut out the core for six inches on the left and stick the end of 1 under *a*, into the place occupied by the core. Next, cut out the core in the same way on the right, and stick the end of *a* in the place of the core. The ends of the strands must be straightened before they are stuck in.

Now loosen the rope nipper and let the wire rope close. Any slight inequality can be taken out by pounding the rope with a wooden mallet.

Next, shift the rope nippers, and repeat the operations at the other five places.

After the rope has run for a day, the locality of the splice can be no longer detected. There are no ends turned under or sticking out, as in ordinary splices, and the rope is not increased

in size, nor appreciably weakened in strength.

I have dwelt so minutely on the process of splicing, because practical experience has demonstrated that a man who can splice a wire rope well, is something of a rarity. Some of the best ship-riggers are utterly non-plussed when a wire rope is presented to them to be spliced; and the splice they produce is usually half again as thick as the rope, and utterly useless for the intended purpose.

When a rope has been well spliced and kept running, its average life is about three years.

Up to this point, I have been speaking of the common wire ropes, as generally made and used for the purpose of transmitting power, viz., wire ropes with hemp centers, and also those with wire centers. The latter have not given satisfactory results, as they wear out very rapidly. The only advantages to be gained by using a wire center rather than one of hemp, are that the same

amount of force may be transmitted with a relatively smaller rope, and that the rope itself stretches less. This latter difficulty can be almost entirely obviated, as will be explained further on; and as the ropes with hemp centers are much more durable, they are now the only ones used. Another disadvantage found in the use of ropes with wire centers, is that the splice must be made nearly twice as long as when hemp is used for the center. This must be done to prevent the two ends of the rope from slipping out, as the co-efficient of friction is not so great between iron and iron, as between iron and hemp.

As in splicing, the wire center is cut off at the splice, and not spliced in, it is free to move in the rope in the direction of least resistance. It consequently happens that the wire center frequently protrudes through the strands of the rope. This may be partly remedied by sewing with cord through the center and the outside wires, thus fastening them in their proper relative positions. In a short

time, however, the center will again project; we are then compelled to cut off the projecting end, and repeat the operation of sewing with cord; which does not by any means improve the durability of the rope. The principal difficulty, the excessive wear of the outer wires, is common to both kinds of ropes. This wear is caused chiefly by the friction of the wire on the sides of the wheel-groove, when the rope, for any reason, runs unsteadily and swings against the sides of the groove. The ropes get flat in places and finally the wires break.

We may keep a transmission in as thorough repair as we will, but we can not prevent, that at times there will be more or less oscillating and swinging of the ropes against the wheel-rim, resulting in the wear above referred to. This evil may be greatly obviated by making the section of the wheel-rim more of the form shown in Fig. 11. But this is attended with several disadvantages, particularly in the case of double-grooved wheels (compare Figs. 12 and 13).

Fig 11

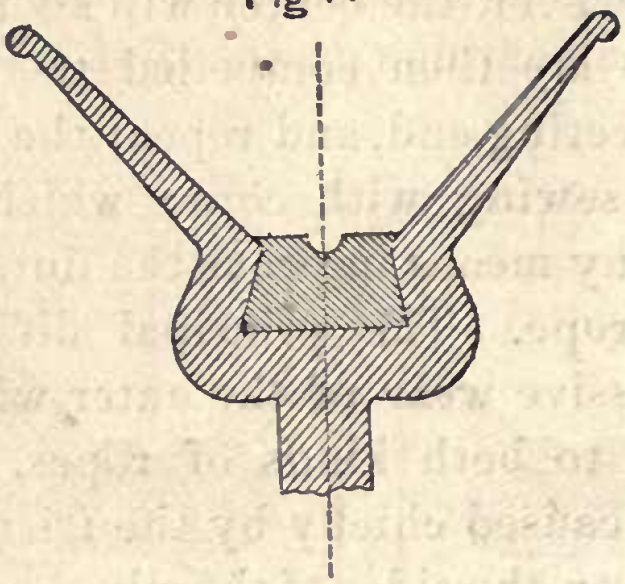
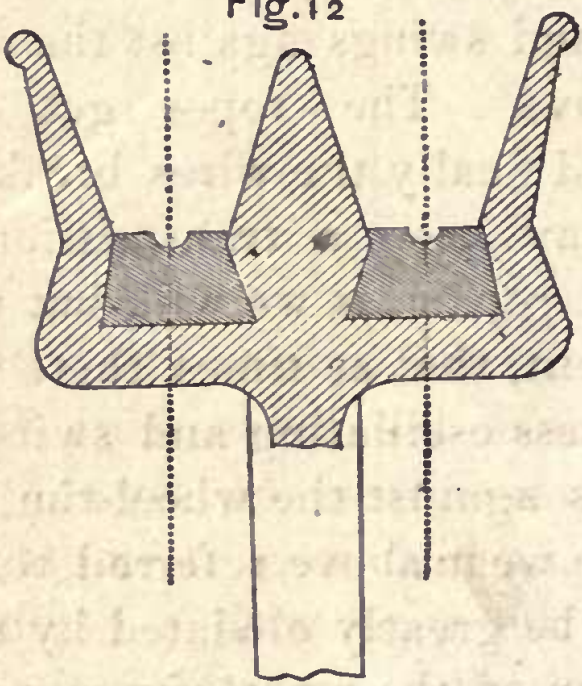


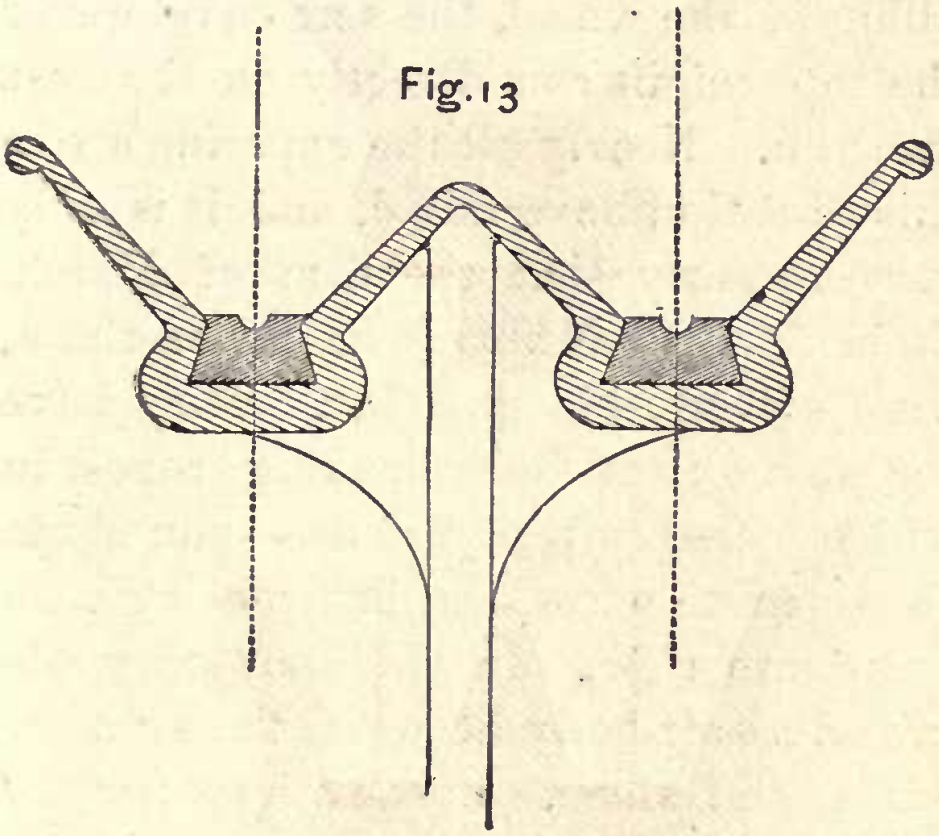
Fig. 12



This would increase the difficulty and expense of making the wheels, and would have the great disadvantage that the distance between the ropes would be great-

er, resulting in a considerable side pressure on the bearings of the shafts.

Fig. 13



To prevent the wear of the wires, and thus to make the ropes more durable, has been the object of several inventions; all of which were attempts at surrounding the wires with a flexible and durable covering, protecting the wires, and at the same time not increasing the difficulties of splicing. It was also thought, that if this could be made a practical success, the filling in the wheels

might be entirely dispensed with. Instead of the rope running on the soft filling of the wheel, the soft envelope of the rope might run directly on the cast iron rim. Nearly all the experiments in this direction have failed, and it is only very recently that the firm of Martin Stein & Co., Mulhausen, Switzerland, have solved this question. They have for some time been making ropes in which coarse cotton yarn was spun about the separate wires, the latter being then spun into rope. In this way they obtained a soft body between the separate wires, and also a soft envelope for the whole rope, which, when saturated with a special resinous compound, is said to be very durable. This kind of covered rope stretches much less than the common rope. Comparisons made, indicate a stretch of only .06 per cent. It also seems less subject to the variation of weather, being partly protected against sun and rain by the covering. For the same reason, rusting is not likely to occur. If, in connection with these covered

ropes, we also employ wheels with leather filling, the adhesive force on the pulleys becomes much greater than in the ordinary ropes; thus allowing the transmission to be worked with much less tension in the ropes. If we desire to get the same cross-sectional area of metal in these ropes as in the common ones, the size of rope required will, of course, be considerably greater, but the rope itself will be much more flexible. In this case, we can, without any harm resulting therefrom, introduce covered wire centres instead of using hemp.

Messrs. Stein & Co. have also been experimenting with hemp as a covering, instead of the expensive cotton yarn, but their experiments are of too recent date to be discussed here.

The price of covered wire ropes is, of course, greater than that of the common ropes. But if they are as durable as the manufacturers claim, *i. e.*, if they may be expected to last about ten years, it is, of course, more true economy to use the more expensive rope. By using

these covered ropes, previously well stretched, we may doubtless avoid the various difficulties which have opposed and prevented the more general introduction of the transmission of power by wire-ropes.

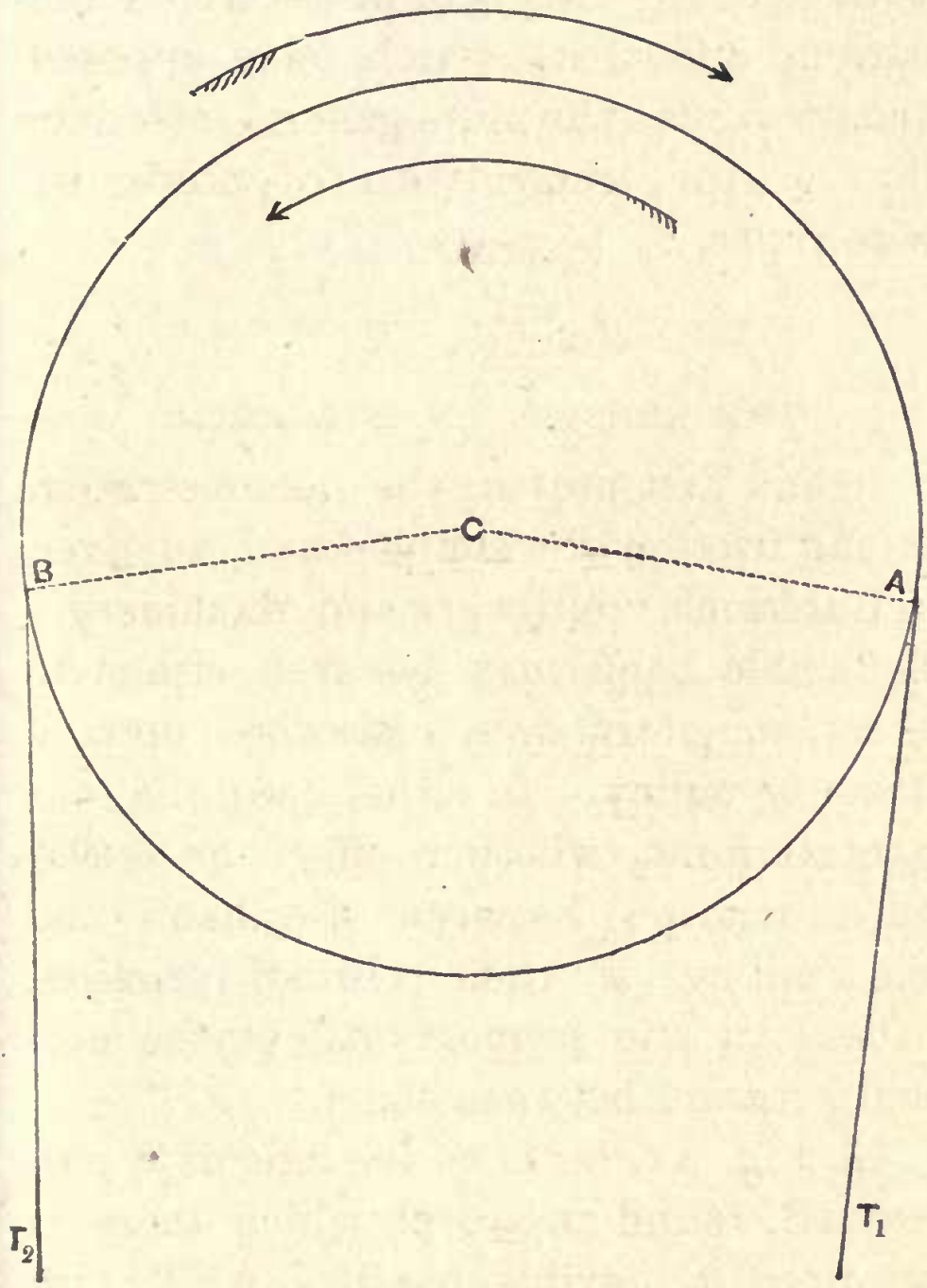
Section IV.

THE TENSION ON THE ROPE.

I shall first present the demonstration of the friction of a simple band, as given in Rankine's "Millwork and Machinery." A flexible band may be used either to exert an effort or a resistance upon a drum or pulley. In either case, the tangential force, whether effort or resistance, exerted between the band and the pulley, is their mutual friction, caused by and proportional to the normal pressure between them.

In Fig. 14, let C be the axis of a pulley AB, round an arc of which there is wrapped a flexible band, T_1ABT_2; let the outer arrow represent the direction in which the band slides, or tends to slide, relatively to the pulley, and the

Fig. 14



inner arrow the direction in which the pulley slides, or tends to slide, relatively to the band. Let T_1, be the tension of

the free part of the band at that side *towards* which it tends to draw the pulley, or *from* which the pulley tends to draw it; T_2, the tension of the free part at the other side; T, the tension of the band at any intermediate point of its arc of contact with the pulley; θ, the ratio of the length of that arc to the radius of the pulley; $d\theta$, the ratio of an indefinitely small element of that arc to the radius; $R = T_1 - T_2$ = the total friction between the band and the pulley; dR, the elementary portion of the friction, due to the elementary arc $d\theta$; f, the coefficient of friction between the materials of the band and pulley. Then it is known that the normal pressure at the elementary arc $d\theta$ is $T d\theta$; T being the mean tension of the band at that elementary arc; consequently the friction on that arc is

$$dR = f T\, d\theta.$$

Now, that friction is also the difference between the tensions of the band at the two ends of the elementary arc; or

$$d\,\mathrm{T} = d\,\mathrm{R} = f\,\mathrm{T}\,d\,\theta;$$

which equation being integrated throughout the entire arc of contact, gives the following formulae:

$$\left.\begin{array}{r} \text{hyp. log.}\ \dfrac{\mathrm{T}_1}{\mathrm{T}_2} = f\,\theta\,;\ \mathrm{T}_1 \div \mathrm{T}_2 = e^{f\,\theta} \\ \mathrm{R}_1 = \mathrm{T}_1 - \mathrm{T}_2 = \mathrm{T}_1(1 - e^{-f\theta}) = \mathrm{T}_2(e^{f\theta} - 1) \end{array}\right\} \quad (1)$$

When a belt connects a pair of pulleys at rest, the tensions of its two sides are equal; and when the pulleys are set in motion, so that one of them drives the other by means of the band, it is found that the advancing side of the belt is exactly as much tightened as the returning side is slackened, so that the *mean* tension remains unchanged. The ratio which it bears to the force, R, to be transmitted, is given by this formula:

$$\frac{\mathrm{T}_1 + \mathrm{T}_2}{2\,\mathrm{R}} = \frac{e^{f\,\theta} + 1}{2\,(e^{f\theta} - 1)} \quad . \quad . \quad . \quad (2)$$

If the arc of contact between the band

and the pulley, expressed in fractions of a turn, be denoted by n, then

$$\theta = 2\pi n; \quad e^{f\theta} = 10^{2.7288 f n} \quad . \quad (3)$$

that is to say, $e^{f\theta}$ is the *antilogarithm*, or natural number, corresponding to the common logarithm $2.7288 f n$.

The value of the coefficient of friction, f, depends on the state and material of the rubbing surfaces. This coefficient is about 0.25 when wire rope is used running on leather or gutta percha. In wire rope transmission $n = \frac{1}{2}$; inserting this value, and also the value of f, in equation (2), we get:

$$\frac{T_1}{T_2} = 2.188; \quad \frac{T_1}{R} = 1.84; \quad \frac{T_1 + T_2}{2R} = 1.34.$$

In ordinary practice, it is usual to assume

$$T_2 = R; \quad T_1 = 2R; \quad \frac{T_1 + T_2}{2R} = 1.5$$

This has been done in the calculations in this thesis. Therefore, if with a wire rope we wish to transmit a certain force

P, we must proportion the transverse dimensions of the rope to bear the maximum strain that will come on it. This maximum strain will come on the driving side of the rope and be equal to twice the force transmitted, *i. e.*, equal 2 P.

In all the following calculations, the strength of the hemp core is left entirely out of consideration, as it is only used for the purpose of securing flexibility, and not for strength. If it is an error to leave this out, it is only a slight one, and is on the safe side at that.

Let P = force to be transmittted.

a = total cross-sectional area of wires in rope in square inches.

t = tension in pounds per square inch of cross-sectional area of wires.

Then $ta = 2\,P$; and $a = \frac{2\,P}{t}$.

n = the number of wires in the rope = 42.

d = diameter of each wire; then

$$n\frac{\pi}{4}d^2 = a = \frac{2\,P}{t}.$$

H.P=number of horse-power to be transmitted.

R=radius of wheel in feet.

N=number of revolutions per minute.

Then, by the proper substitutions, we get:

$$n\frac{\pi}{4}d^2=\frac{2}{t}\times\frac{33000\text{ H. P.}}{2\pi\text{R N}}=\frac{33000\text{ H. P.}}{t\pi\text{R N}} \qquad (4)$$

$$d^2=\frac{132000\text{ H. P.}}{t\,n\,\pi^2\,\text{R N}} \quad . \quad . \quad . \quad . \quad . \quad (5)$$

After substituting for n its value, 42, we get:

$$d=\sqrt{\frac{31.85\text{ H. P.}}{t\,\text{R N}}} \quad . \quad . \quad . \quad (6)$$

To find the value of d from the preceding equations, we must know at the very outset, what is the proper tension to use in the ropes. The tension in the rope is composed of three parts; viz., 1st, the tension necessary to transmit the required amount of power with the velocity of the wheel; 2d, the tension produced by the bending of the rope around the wheel, causing the outer

fibres of each wire to be extended and strained; 3rd, the tension caused by the centrifugal force.

This centrifugal tension, though never amounting to much in ordinary practice, becomes somewhat of an item when a velocity of nearly a mile per minute is employed. It is the sum of these tensions which the rope is called upon to resist.

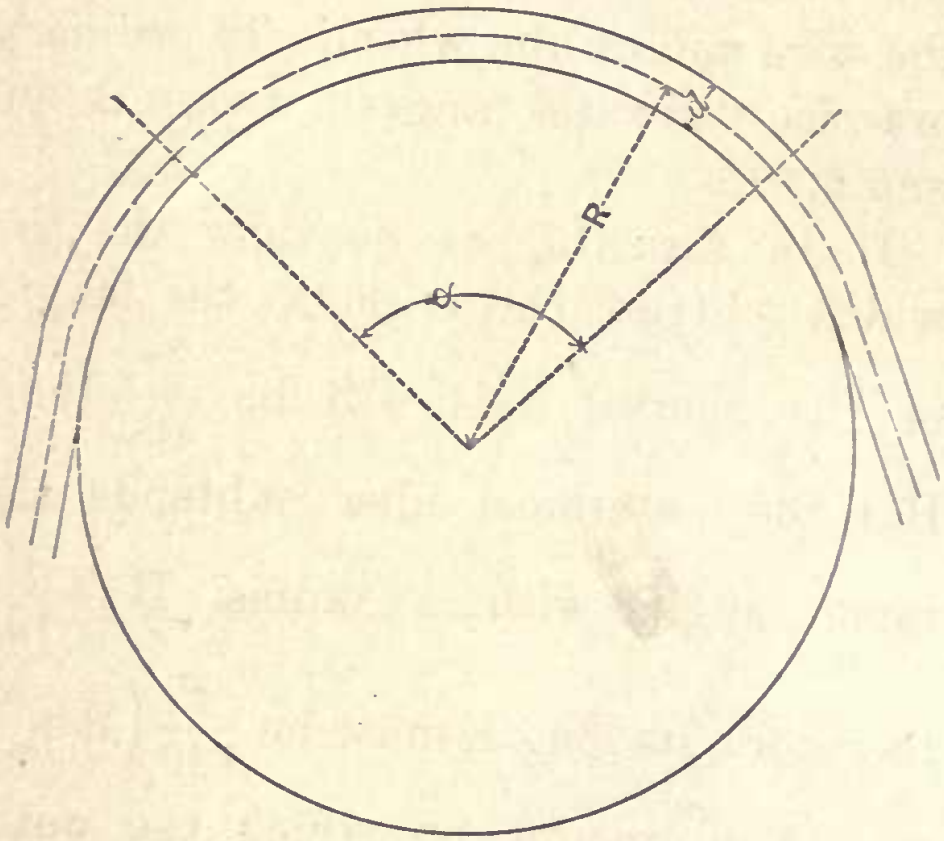
Determining the proper tension is, of course, equivalent to fixing on a factor of safety. Rankine states that three and a half is a good factor for steady work. Although this may at first sight, seem rather low, it must be borne in mind that the process of wire drawing is a process of testing, so that we are certain of having only the best materials. We may, therefore, safely work with this factor, but for the sake of durability, a somewhat higher factor seems advisable. In this thesis, four (4) has been taken as the factor of safety. To find the tension available for the transmission of power, we must evidently get the difference

between the total tension and the sum of the tensions produced by bending and by centrifugal force.

We will, therefore, pass at once to the consideration of the tension caused in the rope, by bending the same around the wheels.

In Figure 15, let R= radius of the

Fig. 15



wheel, d= diameter of a single wire, and E= modulus of elasticity of wire. Now it is apparent that when the rope is

compelled to bend to the curve of the wheel, the outer fibres of each wire will be extended and the inner ones compressed, while the center (the neutral axis) will remain unchanged in length. As the strain varies with the size of the wheel, becoming greater as the wheel is made smaller, and *vice versa*, it is of im portance to determine what should be the relation between the diameters of the wire and of the wheel. In ordinary practice this ratio ranges between 1,000 and 2,500.

If in Fig. 15, we consider the arc which subtends the angle $\propto$, the length of the neutral axis will be $\frac{\pi}{180} R \propto$. But the outermost fiber subtends the same angle with a radius $R + \frac{d}{2}$; therefore, its length must be $\frac{\pi}{180}\left(R+\frac{d}{2}\right) \propto$. The amount by which the outer wire has been extended is evidently the difference between these two lengths; *i. e.*, the extension

$$\lambda = \frac{\pi}{180}\left(R + \frac{d}{2} - R\right)\propto = \frac{\pi}{180} \cdot \frac{d}{2} \propto \quad (7)$$

If t_0 = tension produced in the rope by bending, then, from the definition of the modulus of elasticity, "the quotient obtained by dividing the force which produces the displacement by the amount of the extension," we get

$$E = \frac{t_0 \frac{\pi}{180} R \propto}{\frac{\pi}{180} \frac{d}{2} \propto} = \frac{t_0 R}{\frac{d}{2}} = \frac{2 t_0 R}{d} \quad (8)$$

$$t_0 = \frac{E d}{2 R} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

$$\frac{R}{d} = \frac{E}{2 t_0} \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

From these equations the tension may be determined. For the elasticity of iron wire we may take the mean of various experiments; viz., 28,000,000 lbs. Substituting this value of E and also introducing for d its value $\frac{D}{9}$, we have for the tension per square inch caused by bending

$$t_0 = 28000000\frac{D}{18R} = 1555555\frac{D}{R} \quad . \quad . \quad (11)$$

Substituting in equation (11) some of the probable values of the ratio $\frac{D}{R}$, we get the following table :

$\frac{R}{D}$	t_0	$\frac{R}{D}$	t_0
40	38888	120	12963
45	34570	130	11965
50	31111	140	11111
55	28282	150	10730
60	25925	160	9722
65	23930	170	9150
70	22222	180	8642
75	20740	190	8187
80	19444	200	7777
85	18300	210	7407
90	17284	220	7161
95	16374	230	6763
100	15555	240	6481
110	14141	250	6222

This table is somewhat interesting, as it shows clearly the cause of the rapid wear of the ropes when running on small pulleys. When the ratio $\frac{R}{D}$ is large, the

tension varies but slightly, with small changes in this ratio; while if the latter is below about 100, the tension increases at a much faster rate than $\frac{R}{D}$ decreases.

On the one hand, as the ratio $\frac{R}{D}$ decreases, the wheels become smaller and less expensive; but, on the other hand, we get so great a strain on the ropes that they quickly wear out. We must, therefore, seek to find a point at which the combined resultant economy may be as great as possible. This will be considered further on.

We will now take up the discussion of the centrifugal tension, using the diagram in Fig. 15.

Let R = radius of wheel in feet.

w = weight of the rope per running foot.

v = velocity of the rope in feet per second.

Then the centrifugal force $= \frac{m\,v^2}{R} = \frac{w}{g} \cdot \frac{v^2}{R}$

But the tension in an arc pressed normally by any force p is $p\,\mathrm{R}$; consequently the *centrifugal tension*

$$t_2 = \frac{w}{g} \cdot \frac{v^2\,\mathrm{R}}{\mathrm{R}} = .03106\,wv^2 \quad . \quad . \quad (12)$$

If we wish to express the velocity differently, we may write, when N = number of revolutions per second, $v = 2\,\pi\,\mathrm{R\,N}$, $v^2 = 4\,\pi^2\,\mathrm{R^2\,N^2}$; introducing this value of v^2, we have

$$t_2 = 1.226\,\mathrm{R^2\,N^2}\,w \quad . \quad . \quad . \quad (13)$$

While the rope is passing around the wheel, it is subjected to a tension T, which is equal to the sum of these three separate tensions. But in any given case, we may evidently vary the component tensions at pleasure, provided we keep the total tension T constant.

We have previously (equations (5) and (6)) determined the diameter of the wires in terms of the tension t. But we now wish to introduce the total tension T, into this formula. Bearing in mind that $t = \mathrm{T} - t_0 - t_2$, and multiply-

ng equation (5) by the value of d, in equation (10), we get

$$d^3 = \frac{132000}{\pi^2 n E} \cdot \frac{2 t_0}{T - t_0 - t_2} \times \frac{H P}{N}$$

$$= \frac{264000 \text{ H.P.}}{\pi^2 n E N} \times \frac{t_0}{t} \quad . \quad . \quad (14)$$

Having now obtained an equation introducing the ratio $\frac{t_0}{t}$, we must know how this is to be determined, i.e., what conditions control the magnitude of t_0 and t with respect to T.

(In all the following calculations, the centrifugal tension t_2 is not taken into consideration, as it only amounts to 250 pounds, even in an extreme case. This is a small quantity compared with the other tensions on the rope, and would lead to a needless complication of formulæ). These conditions are two in number; 1st, the size of wheel that may conveniently be employed; 2nd, the resulting deflection or sag in the ropes, the latter being again subject to various conditions, such as the available height, etc.

We will now pass to the consideration of the 1st condition; viz.: the size of the wheels. As previously remarked, the value of R varies immensely with changes of t and t_0. The diameter of the wheel, however, is *always* very large, so that it becomes interesting to know under what conditions it assumes its smallest value. The first step is to obtain a perfectly general formula for R. This is done by multiplying equation (14) by the cube of equation (10) which gives as its result

$$R^3 = \frac{264000 \text{H.P.}}{\pi^2 n N} \cdot \frac{t_0 E}{8 t_0^3 (T - t_0)} \quad . \quad . \quad (15)$$

Differentiating this equation, we get

$$3 R^2 d R = \left(\frac{264000 \text{ H.P} \times E}{8 \pi^2 n N} \right) (2 T t_0 - 3 t_0^2) dt_0$$

To find the conditions under which R will assume its minimum value, we must place the first differential coefficient equal to zero. Doing this, we get, after transposing and reducing

$$2 T t_0 = 3 t_0^2 \quad \therefore \quad t_0 = \tfrac{2}{3} T \quad . \quad . \quad . \quad . \quad (16)$$

$$t = \tfrac{1}{2} t_0 \quad . \quad . \quad . \quad . \quad (17)$$

This relation, being independent of the number of wires and of the shape of the rope, will of course hold good for a rope of any size and of any shape of cross-section. This shows the adaptability of this last formula to ropes of flat or rectangular cross-section, which have been used to a limited extent for transmitting power. From this formula, we see that in the case most favorable to small size of wheels, the tension caused by bending is twice as great as the *direct* tensional strain. The minimum value of R is, however, rarely used in practice, for a reason which will be shown presently. It may, however, be remarked here, that with a small working tension t, the deflection or sag of the rope is greater than that with an increased tension; so that in determining the ratio $\frac{t_0}{t}$ we must take into consideration the available height of the wheels above the ground. This point will be considered in the next section.

Section V.

THE CATENARY.

If a rope or other flexible continuous line be secured at two points and loaded continuously between them according to any law, it will assume some definite curvilinear form. When the load is the weight of the rope only, the curve is called a "catenary."

Suppose that the rope is fixed at the points A and B (see Fig. 16), and that the only force in operation is the weight of the rope, *i. e.* the load is a continuous and direct function of the length of arc. Take the origin of co-ordinates at any point on the curve (C_0), the axis of Y being vertical and the axis of X horizontal. All our forces being in one plane, the axis of Z is of course unnecessary.

Let t' = tension at any point, as a.

t_0 = tension at the origin C_0.

X_0 = horizontal component of the tension at $C_0 = t_0 \frac{dx'}{ds}$

Y_0 = vertical component of the tension at $C_0 = t_0 \frac{dy'}{ds}$

X = horizontal component of applied forces between C_0 and a.

Y = vertical component of applied forces between C_0 and a.

$\frac{dx}{ds}, \frac{dy}{ds}$, will be the cosines of the angles which the curve makes with its respective axes, and resolving t' we have

$t'\frac{dx}{ds}$ = horizontal component of tension,

$t'\frac{dy}{ds}$ = vertical component of tension,

Consequently, from the principles of Mechanics, we must have, for equilibrium

$$\left.\begin{aligned} X + X_0 + t'\frac{dx}{ds} &= 0 \\ Y + Y_0 + t'\frac{dy}{ds} &= 0 \end{aligned}\right\} \quad . \quad . \quad . \quad (18)$$

These equations are perfectly general for any case in which the applied forces are in one plane.

To get a more definite result for the case under consideration, we will take the origin at the lowest point C, and the

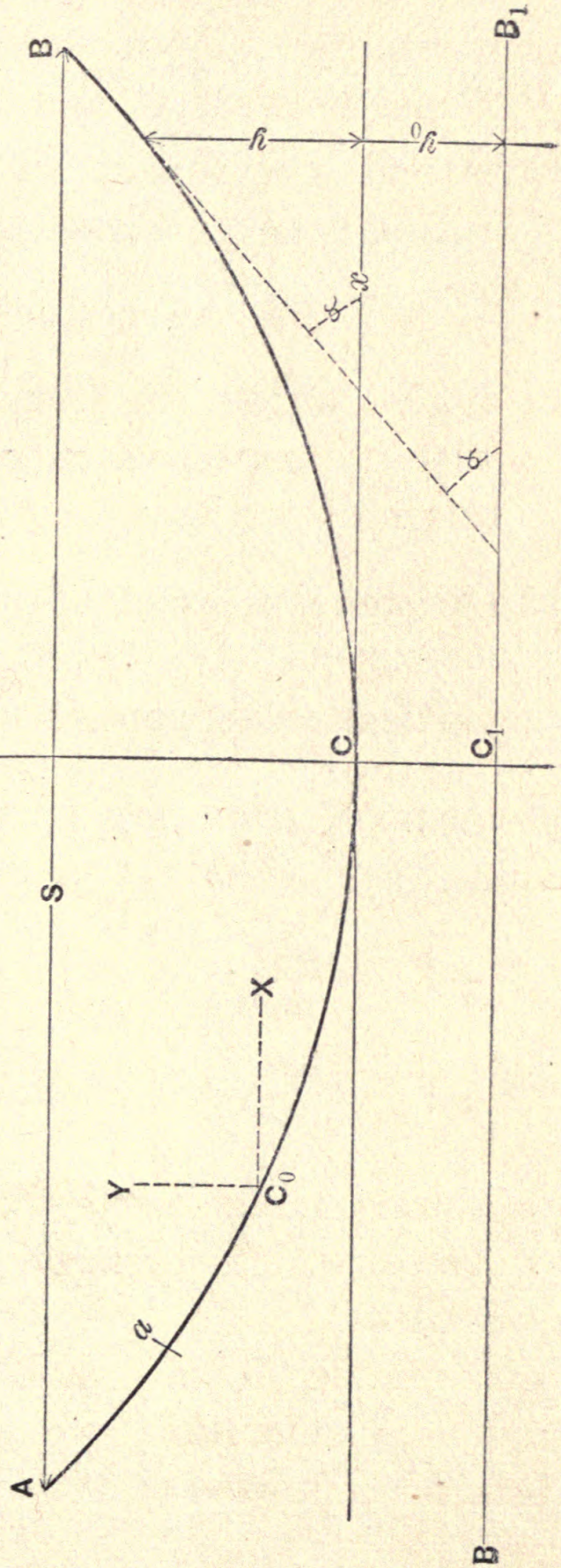


Fig. 16

axis of X tangent to the curve at that point; this will make $\frac{dx'}{ds}=1$ and $\frac{dy'}{ds}=0$; as the weight acts vertically, $X=0$. With these substitutions we get

$$\left.\begin{aligned} t'\frac{dx}{ds}+t_0&=0 \\ Y+t'\frac{dy}{ds}&=0 \end{aligned}\right\} \quad . \quad . \quad . \quad (19)$$

Let w=weight per running foot of rope, and s=length of curve in feet; then ws= weight of the rope; and as this is the only vertical force, we have $ws=Y$.

This reduces the above equations to the following:

$$\left.\begin{aligned} t'\frac{dx}{ds}&=t_0 \\ t'\frac{dy}{ds}&=ws \end{aligned}\right\} \quad . \quad . \quad . \quad (20)$$

Equation (20) shows that the horizontal component of the tension is equal to the tension at the lowest point, *i. e.*, the horizontal component of the tension is constant throughout the curve. We also observe that the vertical component of the tension at any point is equal to the

weight of so much of the rope as comes between the origin and the point considered.

Dividing the first of equations (20) by the second, we get

$$\frac{dx}{dy} = \frac{t_0}{ws} \quad . \quad . \quad . \quad (21)$$

which shows that the tangent of the angle varies inversely as the weight of the rope.

Differentiating equation (21) we have $d\left(\frac{dy}{dx}\right) = \frac{w}{t_0} ds$, but $ds = (dx^2 + dy^2)^{\frac{1}{2}} = \left(1 + \frac{dy^2}{dx^2}\right)^{\frac{1}{2}} dx$. Substituting this value, we have, after transposing

$$\frac{w}{t_0} dx = \frac{d\left(\frac{dy}{dx}\right)}{\left(1 + \frac{dy^2}{dx^2}\right)^{\frac{1}{2}}} \quad . \quad . \quad . \quad (22)$$

Integrating equation (22), we obtain

$$\frac{w}{t_0} x = \text{Nap. log.} \left(\frac{dy}{dx} + \sqrt{1 + \frac{dy^2}{dx^2}}\right)$$

This may be written $e^{\frac{wx}{t_0}} = \frac{dy}{dx} + \sqrt{1 + \frac{dy^2}{dx^2}}$;

transposing, we get

$$e^{\frac{wx}{t_0}} - \frac{dy}{dx} = \left(1 + \frac{dy^2}{dx^2}\right)^{\frac{1}{2}}$$

Squaring this equation we get

$$e^{\frac{2wx}{t_0}} - 2e^{\frac{wx}{t_0}}\frac{dy}{dx} + \frac{dy^2}{dx^2} = 1 + \frac{dy^2}{dx^2} \quad . \quad . \quad (23)$$

Reducing and clearing of fractions, we get

$$dy = \tfrac{1}{2}\left\{e^{\frac{wx}{t_0}} - e^{\frac{-wx}{t_0}}\right\} dx \quad . \quad (24)$$

Integrating the above equation, we obtain

$$y = \frac{t_0}{2w}\left\{e^{\frac{wx}{t_0}} + e^{\frac{-wx}{t_0}}\right\} + \left\{C = -\frac{t_0}{w}\right\}$$

$$\therefore\ y + \frac{t_0}{w} = \frac{t_0}{2w}\left\{e^{\frac{wx}{t_0}} + e^{\frac{-wx}{t_0}}\right\} \quad . \quad (25)$$

which is the equation of the catenary. To bring this equation into a simpler and more manageable form, we will transfer the origin of coordinates to C_1,

making $C C_1 = \frac{t_0}{w}$. Then our new ordinates will be equal to $y + \frac{t_0}{w}$, so that the last equation may be written

$$y_0 = \frac{t_0}{2w}\left\{ e^{\frac{wx}{t_0}} + e^{\frac{-wx}{t_0}} \right\} \quad . \quad . \quad . \quad (26)$$

But in making this change of origin, $\frac{dy}{dx}$, the tangent of the angle α evidently remains constant, and having previously found $\frac{dy}{dx} = \frac{ws}{t_0}$, we will substitute this value in equation (24), giving rise to the following value for the length of arc:

$$S = \frac{t_0}{2w}\left\{ e^{\frac{wx}{t_0}} - e^{\frac{-wx}{t_0}} \right\} \quad . \quad (27)$$

Squaring equations (26) and (27), we get

$$y_0^2 = \frac{t_0^2}{4w^2}\left\{ e^{\frac{2wx}{t_0}} + 2 + e^{\frac{-2wx}{t_0}} \right\} \quad . \quad (26a)$$

$$S^2=\frac{t_0^2}{4\,w^2}\left\{e^{\frac{2\,wx}{t_0}}-2+e^{\frac{-2\,wx}{t_0}}\right\}. \quad (27a)$$

Subtracting (27a) from (26a), we have

$$y_0^2-S^2=\frac{t_0^2}{w^2}$$

$$S=\sqrt{y_0^2-\frac{t_0^2}{w^2}} \quad . \quad . \quad . \quad (28)$$

Equation (28) gives us the length of arc when the running weight of the rope, and the ratio $\frac{t_0}{w}$, are known. The weight of the rope is always known in any given case.

To find the value of $\frac{t_0}{w}$, we proceed as follows:

Let Δ = total deflection or greatest ordinate of the curve.

S = span between supports.

Then, for the lowest point, the ordinate is $y_0=\Delta+\frac{t_0}{w}$; and the abscissa $x=\frac{1}{2}$ S. Substituting these values in equation (26) and reducing, we get

$$\frac{t_0}{w}=\frac{2\,\Delta}{e^{\frac{w\,S}{2\,t_0}}+e^{\frac{-w\,S}{2t_0}}-2} \quad . \quad . \quad . \quad (29)$$

The equation just found is not susceptible of a direct solution; so that it becomes necessary to find the value of $\frac{t_0}{w}$ by a method of approximation. This will be done in the next section (VI).

Let L=total length of rope between supports; then from equation (28),

$$\mathrm{L}=2\sqrt{\left(\Delta+\frac{t_0}{w}\right)^2-\frac{t_0^{\,2}}{w^2}}=2\sqrt{\Delta^2+\frac{2\,\Delta\,t_0}{w}} \quad (30)$$

To find the tension at any point, we know that from the parallelogram of forces

$$t'^2=\left(t'\frac{dy}{ds}\right)^2+\left(t'\frac{dx}{ds}\right)^2.$$

We substitute in this equation the values obtained from equation (20), and get

$$t'^2=w^2s^2+t_0^{\,2}=w^2\left(y_0^{\,2}-\frac{t_0^{\,2}}{w^2}\right)+t_0^{\,2}=w^2y_0^{\,2}$$

$$t'=wy_0 \quad . \quad . \quad . \quad . \quad . \quad (31)$$

The tension t' is a maximum at the highest points. The ordinates for these points being $\triangle + \frac{t_0}{w}$, we have

$$t' = w\left(\triangle + \frac{t_0}{w}\right) = w\triangle + t_0 \quad . \quad . \quad (32)$$

The vertical component of the tension at the highest point is, of course,

$$ws = w\sqrt{y_0^2 - \frac{t_0^2}{w^2}} = \sqrt{w^2 y_0^2 - t_0^2} \quad . \quad (33)$$

The tangent of the angle α, which the curve, at the highest point, makes with the axis of X, is $\tan \alpha = \frac{ws}{t_0} = \frac{wL}{2t_0} =$

$$\frac{w}{t}\left(\triangle^2 + \frac{2\triangle t_0}{w}\right)^{\frac{1}{2}} = \left(\frac{w^2\triangle^2}{t_0^2} + \frac{2w\triangle}{t_0}\right)^{\frac{1}{2}} \quad . \quad (34)$$

We have now developed all the necessary equations of the catenary; but before applying them, a few remarks on the peculiarities of the curve, as shown by its equations, may not be out of place.

Equation (26) shows that the catenary rises symmetrically on both sides of the

axis of Y, and becomes parallel to the same only at an infinite distance.

The angle α increases with the ordinate y; when y becomes infinite, $\alpha = 90°$; when $y = o$, $\alpha = o$.

The line CC_1, $\left(=\frac{t_0}{w}\right)$ is called the parameter of the curve; and the line BB_1, last used as the axis of abscissas, is called the directrix.

The value of the ratio $\frac{t_0}{w}$ varies between zero and infinity. $\frac{t_0}{w} = o$ when $\Delta = \infty$; for in this case the two exponents in equation (26) also become zero; $\frac{t_0}{w} = \infty$, when $\Delta = o$, because the two exponents then each equal unity. The value of $\frac{t_0}{w}$ is always very large, when Δ is small, as it always is in transmitting power by wire rope.

As will be seen from equations (31) and (32), the tension in the rope is directly proportional to the weight of the

latter. The tension reaches its maximum at A and B, and has its minimum at C, where $t' = t_0$.

When Δ is small, there is very little difference between t_0 and t'; and as w is always very large, the results obtained from equations (29) and (31) will not differ greatly.

The tension $t' = t_0 = \infty$, when $\Delta = o$; this shows the impossibility of stretching a rope so as to be perfectly horizontal; because even when it is hauled as taut as may be, there must always be a finite value of Δ existing.

Section VI.

Approximate solution of catenary.

In practically applying the preceding equations of the catenary, we meet with considerable difficulty, which is owing to the fact that the parameter $\frac{t_0}{w}$ can only be obtained from a transcendental equation.

But in such work as forms the subject of this thesis, we can pursue a frequently used method of approximation, which is abundantly accurate for all our purposes. The exact equations of the catenary, as we have deduced them, are of course applicable; but, as we have left the stiffness of the rope out of consideration, and assumed it to be "perfectly flexible," the shape of the curve is not expressed with mathematical exactitude by even these equations. For this reason alone, it might be permissible to use approximate formulæ; but we have a still greater right to use them, because the deflection $\triangle$ is always a very small fraction of the span S, and, therefore, the parameter $\frac{t_0}{w}$ is always very large.

Consequently, in equation (29), the exponent $\frac{w\,S}{2\,t_0}$ is a small fraction; and we can, without committing any great error, express its value by the series

$$e^{\frac{w\,S}{2\,t_0}} = 1 + \frac{w\,S}{2\,t_0} + \frac{w^2 S^2}{2 \times 4 t_0^2} + 2\frac{w^3\,S^3}{\times 3 \times 8\,t_0^3} +$$

$$e^{-\frac{w\,S}{2\,t_0}} = 1 - \frac{w\,S}{2\,t_0} + \frac{w^2\,S^2}{2\times 4 t_0^2} - \frac{w^3\,S^3}{2\times 3\times 8\,t_0^3} +$$

Taking the first four terms of these series, and substituting them in equation (29), we get

$$\frac{t_0}{w} = \frac{2\,\Delta}{2 + \frac{w^2\,S^2}{4\,t_0^2} - 2} = \frac{2\,\Delta}{\frac{w^2\,S^2}{4\,t_0^2}} = \frac{S^2}{8\,\Delta} \quad . \quad (35)$$

Substituting the same terms of a similar series in equation (26), we get

$$y_0 = \frac{t_0}{2\,w}\left(2 + \frac{w^2\,x^2}{2\,t_0^2}\right) = \frac{t_0}{w} + \frac{w x^2}{4\,t_0}$$

$$y_0 - \frac{t_0}{w} = \frac{w x^2}{4\,t_0}$$

$$y_0 - \frac{S^2}{8\,\Delta} = \frac{w x^2}{4\,t_0} \quad . \quad . \quad . \quad . \quad . \quad (36)$$

This is the equation of a parabola having a parameter of $\frac{S^2}{4\,\Delta}$; so that our method of approximation has led us to consider the curve as a parabola.

Substituting the value $\frac{t_0}{w} = \frac{S^2}{8\,\Delta}$ in equa-

tion (30), we get for the length of the curve between supports

$$L=2\sqrt{\triangle^2+\frac{2\triangle S^2}{8\triangle}}=2\sqrt{\triangle^2+\frac{S^2}{4}} \quad . \quad (37)$$

By reference to the figure, it will be seen that this is equivalent to assuming that the length of the curve is equal to twice the length of the chord of half the curve. All the formulæ previously found now become, by the proper substitutions

$$t'=w\left(\triangle+\frac{S^2}{8\triangle}\right) \quad . \quad . \quad . \quad . \quad (38)$$

$$t_0=\frac{w\,S^2}{8\triangle} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (39)$$

$$t'\frac{dy}{dx}=w\left(\triangle^2+\frac{S^2}{4}\right)^{\frac{1}{2}} \quad . \quad . \quad . \quad (40)$$

$$\text{tan. } \alpha=\frac{8\triangle}{S^2}\left(\triangle^2+\frac{S^2}{4}\right)^{\frac{1}{2}} \quad . \quad . \quad . \quad (41)$$

By means of these formulæ, it becomes an easy matter to investigate the various problems which present themselves.

Section VII.

DEFLECTION OF THE ROPE.

In order that the rope may be subjected to a proper tension, the deflection or sag must be of a certain magnitude while the rope is at rest; we must also know the sag of the rope while in motion, in order to estimate the necessary elevation of the wheels. There are therefore three deflections which we must determine: 1st, that of the driving side while in motion; 2nd, that of the following side while in motion; 3rd, that of both sides when the rope is at rest. Let the deflection at rest be called Δ_0. When we start one of wheels, the driving side of the rope rises and the following side is depressed, until the difference of their tensions is equal to the force to be transmitted, when the driven wheel will begin to move; in this condition we will call the deflection of the driving side Δ_1 and that of the following side Δ_2.

We must know the deflection at rest,

Δ_0, in order to determine the proper length of rope; so that when it is put on and spliced, we may feel certain, that there will be neither any slipping during the motion, nor any serious strain on the rope itself. The deflections Δ_1 and Δ_2, as before stated, must be known, in order to determine in advance, what position the ropes will take while in motion, how near they will approach the ground or other obstructions, and how many, if any, carrying sheaves are required.

By solving equation (38) for Δ, we get for the value of the deflection

$$\Delta = \frac{t'}{2w} - \sqrt{\left(\frac{t'}{2w}\right)^2 - \frac{S^2}{8}} \quad . \quad . \quad (42)$$

Now, we have seen in Section IV, that if the force at the circumference of the wheel is P, then to find the deflection Δ_1 of the driving side, $t' = 2P$. To find the deflection Δ_2 of the following side, $t' = P$. Lastly, to find the deflections Δ_0 of both sides while at rest $t' = \frac{3}{4}P$.

In applying equation (42) and all other

equations containing t', it is to be borne in mind that t' is not the tension per square inch, but is the whole tension on the rope.

From this equation, it is evident that the tension has a great influence on the deflection of the rope. This is best shown by an example. Suppose that, with a span of 400 feet, we are using a $\frac{11}{16}$ inch rope working under a tension of 3,000 pounds. By making the proper substitutions in equation (42) we get

$$\Delta = \frac{3000}{1.372} - \sqrt{\left(\frac{3000}{1.372}\right)^2 - \frac{(400)^2}{8}} = 2.8 \text{ ft.}$$

Now if we had the same rope working under a tension of only 2,400 pounds, the deflection would be

$$\Delta = \frac{2400}{1.372} - \sqrt{\left(\frac{2400}{1.372}\right)^2 - \frac{(400)^2}{8}} = 5.8 \text{ ft.}$$

Thus, a difference in tension of only 600 pounds, causes a difference in deflection of three feet.

In both these cases, the rope will work equally well, if the size of the wheel has been properly selected; but in most

cases, it is not a matter of indifference whether the rope has a deflection of two feet or of five feet.

The smaller deflection is usually to be preferred, as it requires a less elevation for the wheels. On the other hand, with a very short span the greater deflection is generally preferable.

It is, therefore, evident that we cannot decide on any definite tension to be used in all cases, but that we must select it for every different case, using a greater tension as we want a less deflection, and *vice versa*.

But in order that the rope may work equally well in any case, we must, as previously explained, keep the *sum* of the various tensions constant, *i. e.*, equal to the ultimate strength of the rope divided by the factor of safety. By a proper adjustment of the tension, we can, in nearly all cases, bring the deflection to any desired amount; but there is still another way to accomplish this end, as follows:

Generally, we are not compelled to

make the upper side of the driving rope act as the driving side, but we can often use the lower side for this purpose. In that case the greater deflection of the lower side takes place while the rope is at rest (See Fig. 17). When in motion, the lower side rises above this position, and the upper side sinks, thus enabling us to avoid obstructions, which, by the other way would have to be removed. Of course this expedient cannot always be employed, as the upper side of the rope must not be allowed to sink so far as to pass below or even to touch the lower side. If this occurs, the rope begins to sway and jerk in a serious manner, wearing out very rapidly.

The shortest distance between the ropes is $2\ R - (\Delta_2 - \Delta_1)$. We must, therefore, always be careful, in using this plan, to see that $2\ R > \Delta_2 - \Delta_1$. This result may often be obtained by a judicious selection of the tension, and of the diameter of wheel.

By the application of the equations given in this and the preceding sections,

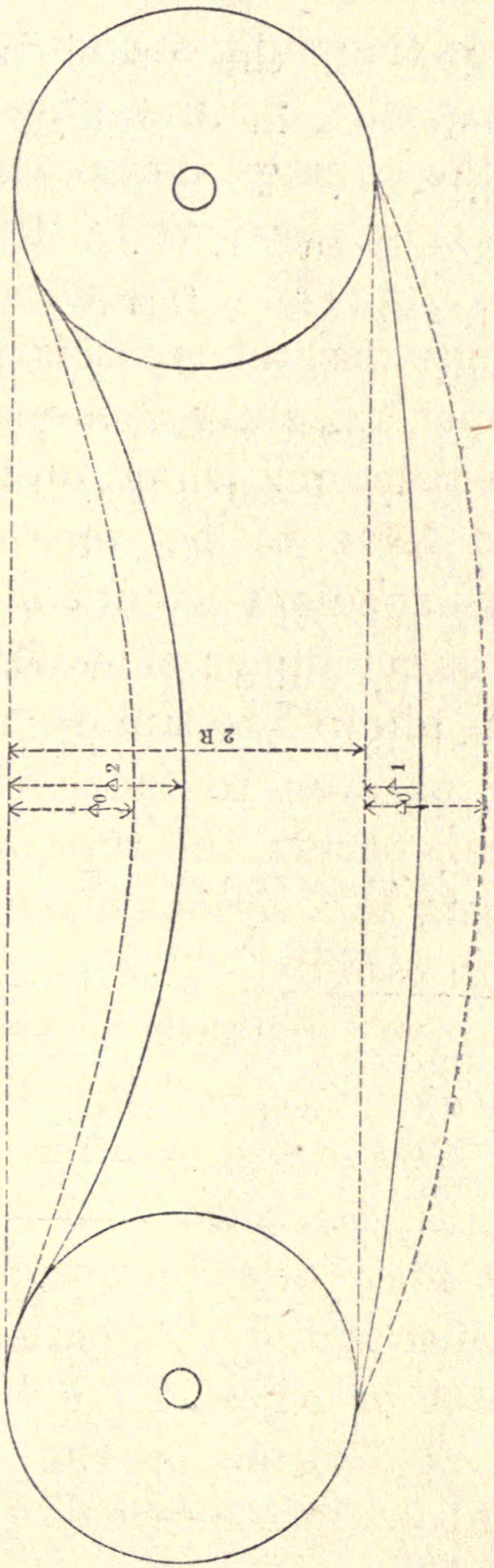


Fig 17

we may solve all the problems which present themselves in designing a wire-rope transmission. The following table which is taken from Mr. W. A. Roebling's pamphlet, previously referred to, will be found of great value in designing, giving as it does, the most suitable proportion for general use. Its use is self-evident; and it need only be remarked, that where there is a choice between a small wheel with fast speed, and a larger wheel with slower speed, it is usually preferable to take the larger wheel.

TABLE OF TRANSMISSION OF POWER BY WIRE-ROPES.

Diameter of Wheel in Feet.	Number of Revolutions.	Trade No. of Rope.	Diameter of Rope.	Horse Power.
4	80	23	$\frac{3}{8}$	3.3
4	100	23	$\frac{3}{8}$	4.1
4	120	23	$\frac{3}{8}$	5.
4	140	23	$\frac{3}{8}$	5.8
5	80	22	$\frac{7}{16}$	6.9
5	100	22	$\frac{7}{16}$	8.6
5	120	22	$\frac{7}{16}$	10.3
5	140	22	$\frac{7}{16}$	12.1
6	80	21	$\frac{15}{32}$	10.7

Diameter of Wheel in Feet.	Number of Revolutions.	Trade No. of Rope.	Diameter of Rope.	Horse Power.
6	100	21	$\frac{15}{32}$	13.4
6	120	21	$\frac{15}{32}$	16.1
6	140	21	$\frac{15}{32}$	18.7
7	80	20	$\frac{1}{2}$	16.9
7	100	20	$\frac{1}{2}$	21.1
7	120	20	$\frac{1}{2}$	25.3
7	140	20	$\frac{1}{2}$	29.6
8	80	19	$\frac{5}{8}$	22.
8	100	19	$\frac{5}{8}$	27.5
8	120	19	$\frac{5}{8}$	33.
8	140	19	$\frac{5}{8}$	38.5
9	80	20		40.
		19	$\frac{1}{2}$ $\frac{5}{8}$	41.5
9	100	20		50.
		19	$\frac{1}{2}$ $\frac{5}{8}$	51.9
9	120	20		60.
		19	$\frac{1}{2}$ $\frac{5}{8}$	62.2
9	140	20		70.
		19	$\frac{1}{2}$ $\frac{5}{8}$	72.6
10	80	19		55.
		18	$\frac{5}{8}$ $\frac{11}{16}$	58.4
10	100	19		68.7
		18	$\frac{5}{8}$ $\frac{11}{16}$	73.
10	120	19		82.5
		18	$\frac{5}{8}$ $\frac{11}{16}$	87.6
10	140	19		96.2
		18	$\frac{5}{8}$ $\frac{11}{16}$	102.2
11	80	19	$\frac{5}{8}$ $\frac{11}{16}$	64.9
		18		75.5
11	100	19	$\frac{5}{8}$ $\frac{11}{16}$	81.1
		18		94.4

Diameter of Wheel in Feet.	Number of Revolutions.	Trade No. of Rope.	Diameter of Rope.	Horse Power.
11	120	19	$\frac{5}{8}$ $\frac{11}{16}$	97.3
		18		113.3
11	140	19	$\frac{5}{8}$ $\frac{11}{16}$	113.6
		18		132.1
12	80	18	$\frac{11}{16}$ $\frac{3}{4}$	93.4
		17		99.3
12	100	18	$\frac{11}{16}$ $\frac{3}{4}$	116.7
		17		124.1
12	120	18	$\frac{11}{16}$ $\frac{3}{4}$	140.1
		17		148.9
12	140	18	$\frac{11}{16}$ $\frac{3}{4}$	163.5
		17		173.7
13	80	18	$\frac{11}{16}$ $\frac{3}{4}$	112.
		17		122.6
13	100	18	$\frac{11}{16}$ $\frac{3}{4}$	140.
		17		153.1
13	120	18	$\frac{11}{16}$ $\frac{3}{4}$	168.
		17		183.9
14	80	17	$\frac{3}{4}$ $\frac{7}{8}$	148.
		16		141.
14	100	17	$\frac{3}{4}$ $\frac{7}{8}$	185.
		16		176.
14	120	17	$\frac{3}{4}$ $\frac{7}{8}$	222.
		16		211.
15	80	17	$\frac{3}{4}$ $\frac{7}{8}$	217.
		16		217.
15	100	17	$\frac{3}{4}$ $\frac{7}{8}$	259.
		16		259.
15	120	17	$\frac{3}{4}$ $\frac{7}{8}$	300.
		16		300.

Section VIII.

LIMITS OF SPAN.

It becomes interesting to know between what limits the span may vary, without giving impracticable results.

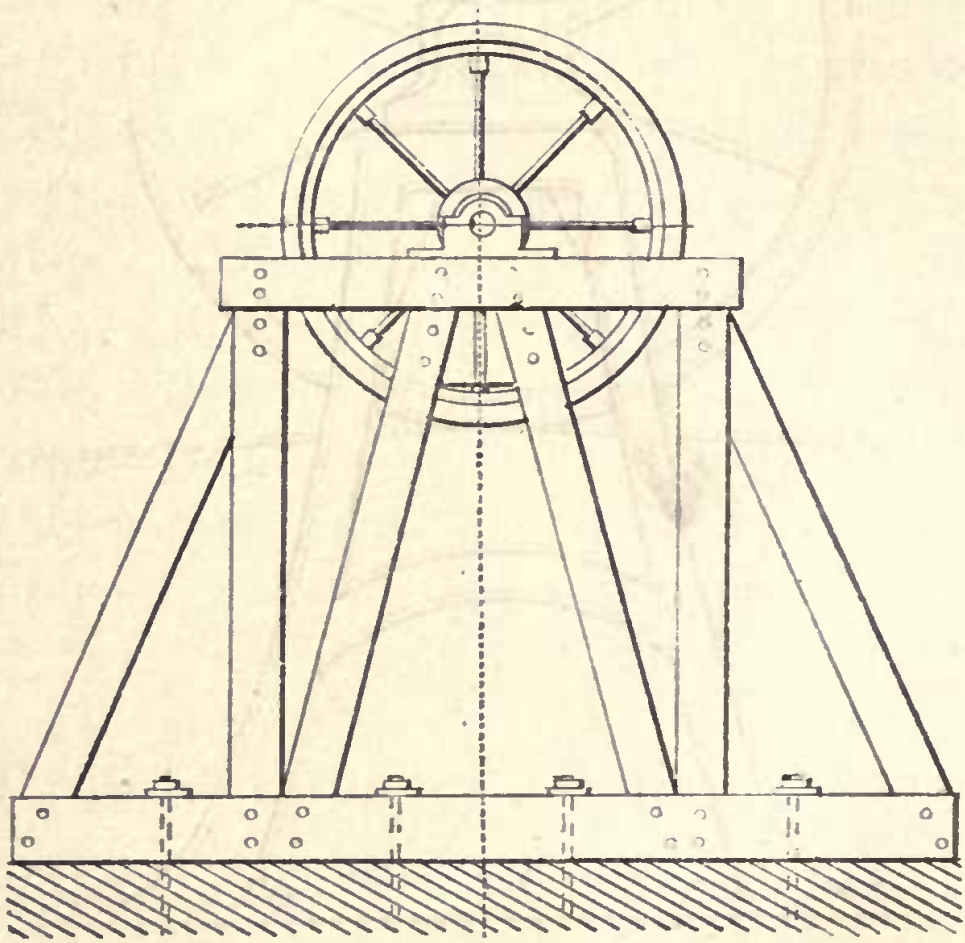
The least practicable span is that in which the deflection of the rope becomes so small, that the latter cannot be hung freely on the driving wheels, so that special tightening devices must be used. As such may be mentioned tightening sheaves and moveable pillow-blocks. Of course it cannot be claimed that such devices make the transmission too complicated, but this merely changes the investigation for the lower limit of the span into one for the limit at which such special devices become necessary. To find the minimum value of the span we proceed as follows: From equation (38) we get an expression for the span in terms of t', w and Δ.

$$S = \sqrt{8\,\Delta\left(\frac{t'}{w} - \Delta\right)} \quad . \quad . \quad . \quad (43)$$

By placing the minimum allowable

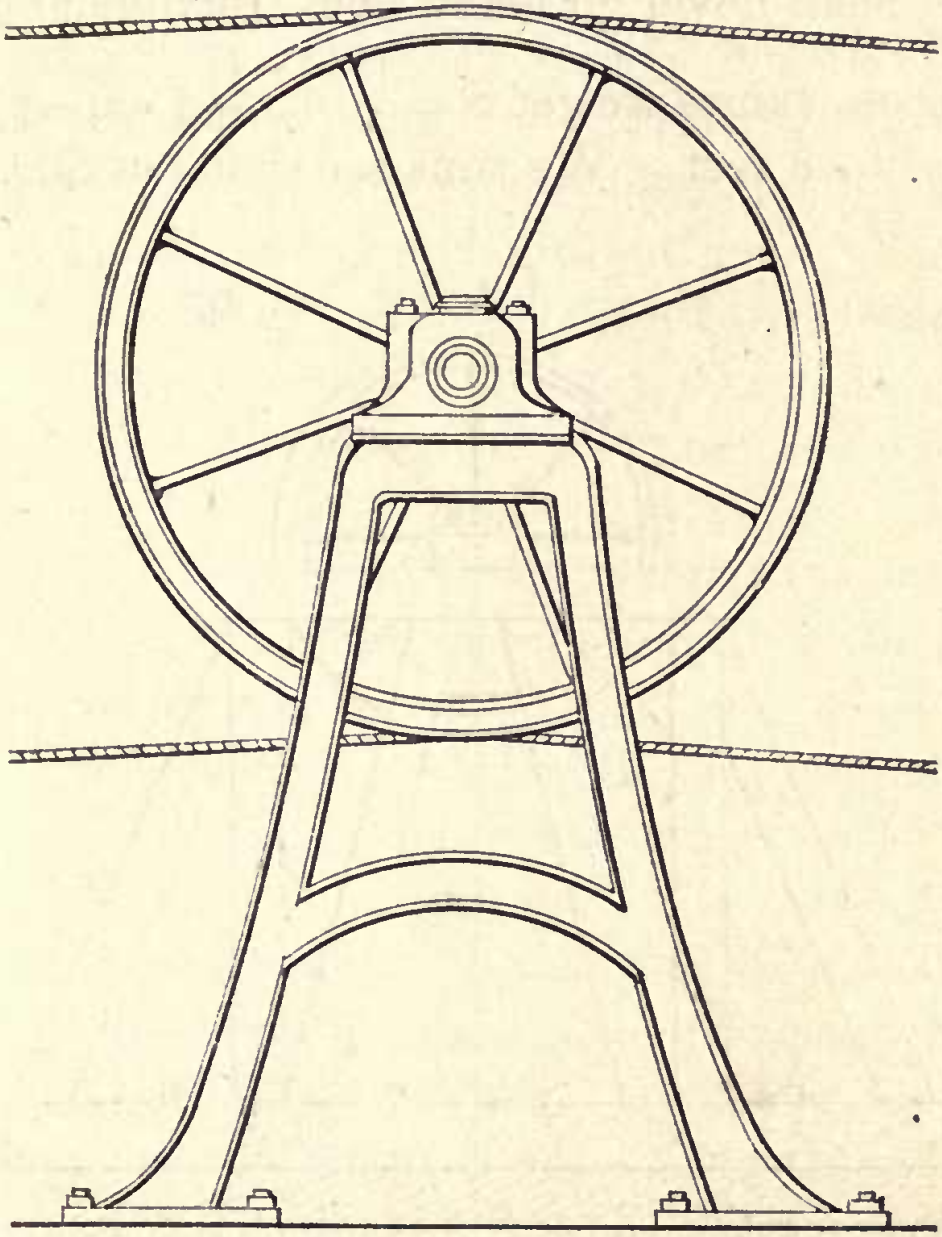
values of Δ and $\frac{t'}{w}$ in this equation, we will get an expression for the smallest value of S. We will therefore assume that the deflection shall never be less than 8 inches $= \frac{2}{3}$ foot, and that the ratio $\frac{t'}{w}$ shall never go below 500. Introducing these values we get $S = \sqrt{8 \times \frac{2}{3} (500 - \frac{2}{3})}$ $= 51.6$ feet. We thus see that the limit

Fig. 18



is very low, allowing us to use a free transmission for so short a distance as 51 feet. Below this, shafting will usually be found preferable and less troublesome.

Fig. 19



When the distance of transmission materially exceeds three or four hundred feet, or when there is not sufficient height available for the sag of the rope, the latter must be supported at intermediate points by *carrying sheaves.* Sometimes it is sufficient to support only the lower following side of the rope, and generally, whatever the number of sheaves, the driving side is supported at one less point than the following side. The same number of sheaves may, however, be used, placing one over the other. The sheaves must never be placed side by side, as has been sometimes done to the great detriment of the transmission. To save still more room, we may, where practicable, make the lower rope the driving side, as previously explained.

The manner of arranging carrying sheaves and intermediate stations is shown in Figures 18–29 inclusive. The sheaves supporting the driving side of the rope must in all cases be of equal diameter with the driving wheels; and this for the same reason that the latter

are usually made of so large a diameter. For whether the rope laps half way round on the driving wheels, or only quarter way round on the carrying sheaves, makes no difference; the tension due to bending is the same in both cases. With the following side, however, a somewhat smaller wheel may be used, owing to the fact that there is less strain on this side, and it is therefore better able to stand the additional tension due to bending.

The system of carrying sheaves may generally be replaced by that of intermediate stations. When this is used, we have at each station, instead of two carrying sheaves, one double grooved wheel. The rope, instead of running the whole length of the transmission, runs only from one station to the other. It is advisable to make the stations equidistant, so that a rope may be kept on hand, ready spliced, to put on the wheels of any span, should its rope give out. This method is greatly to be preferred where there is sometimes a jerking motion to the rope, as it prevents the rope from

Fig.20

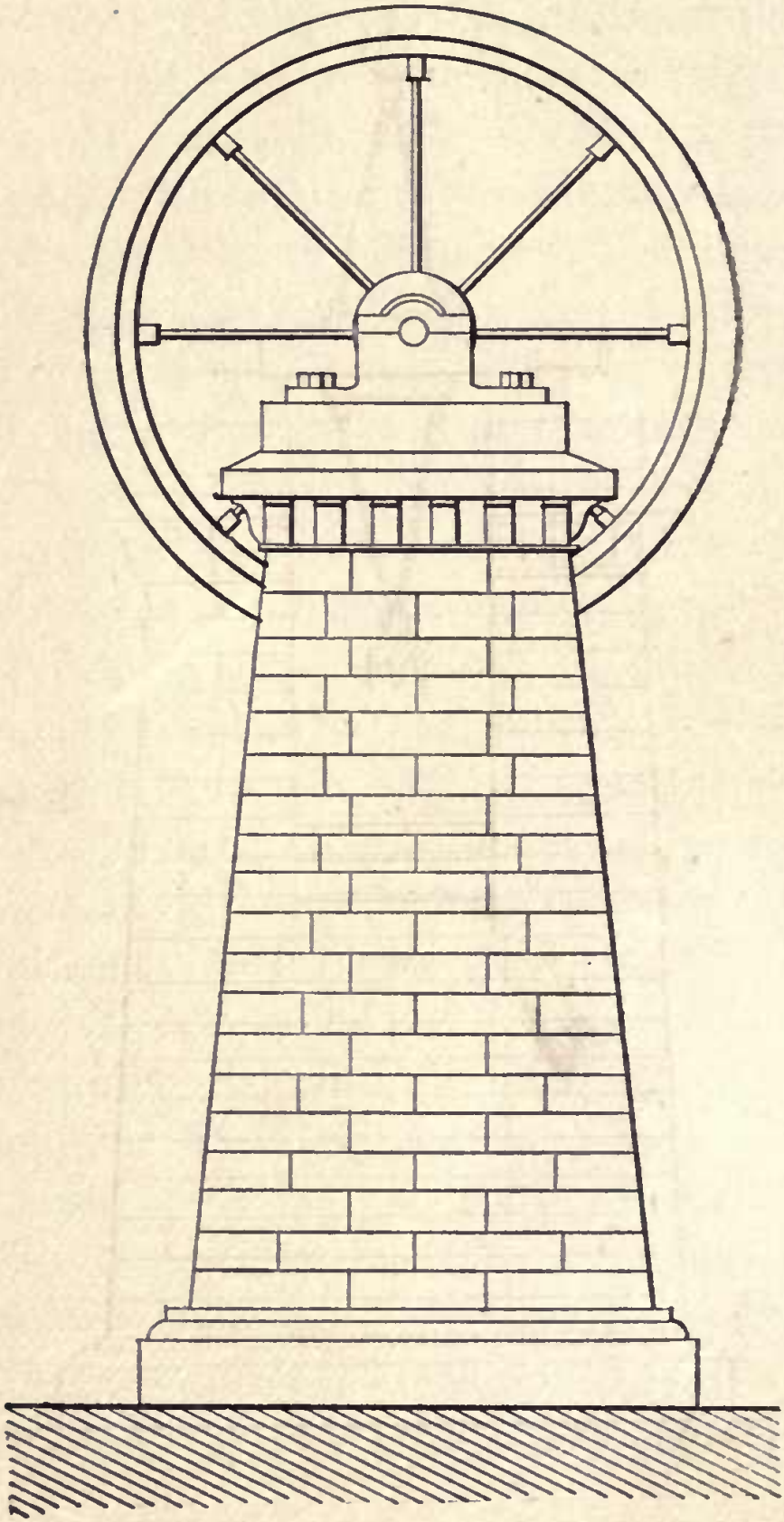
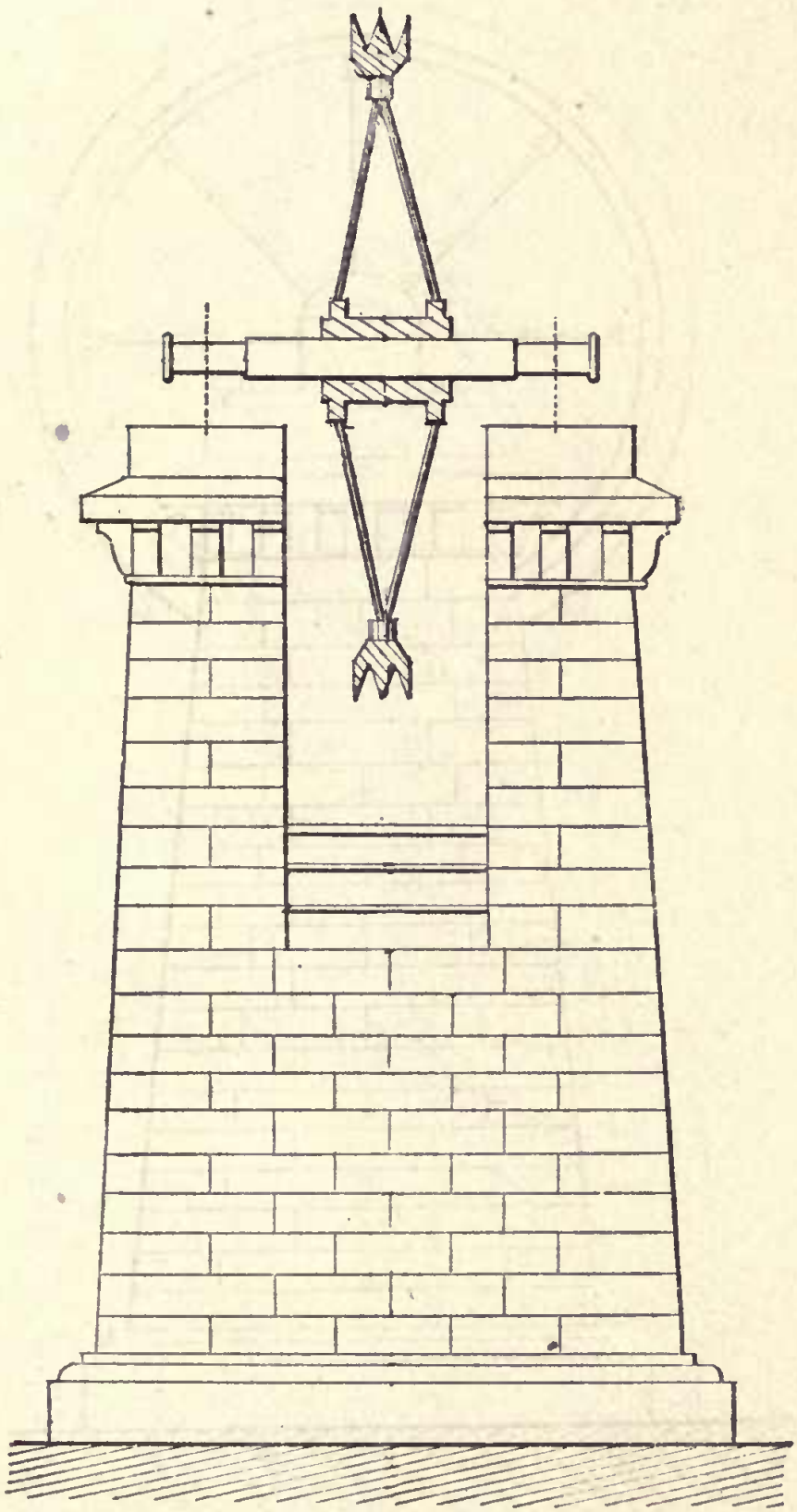


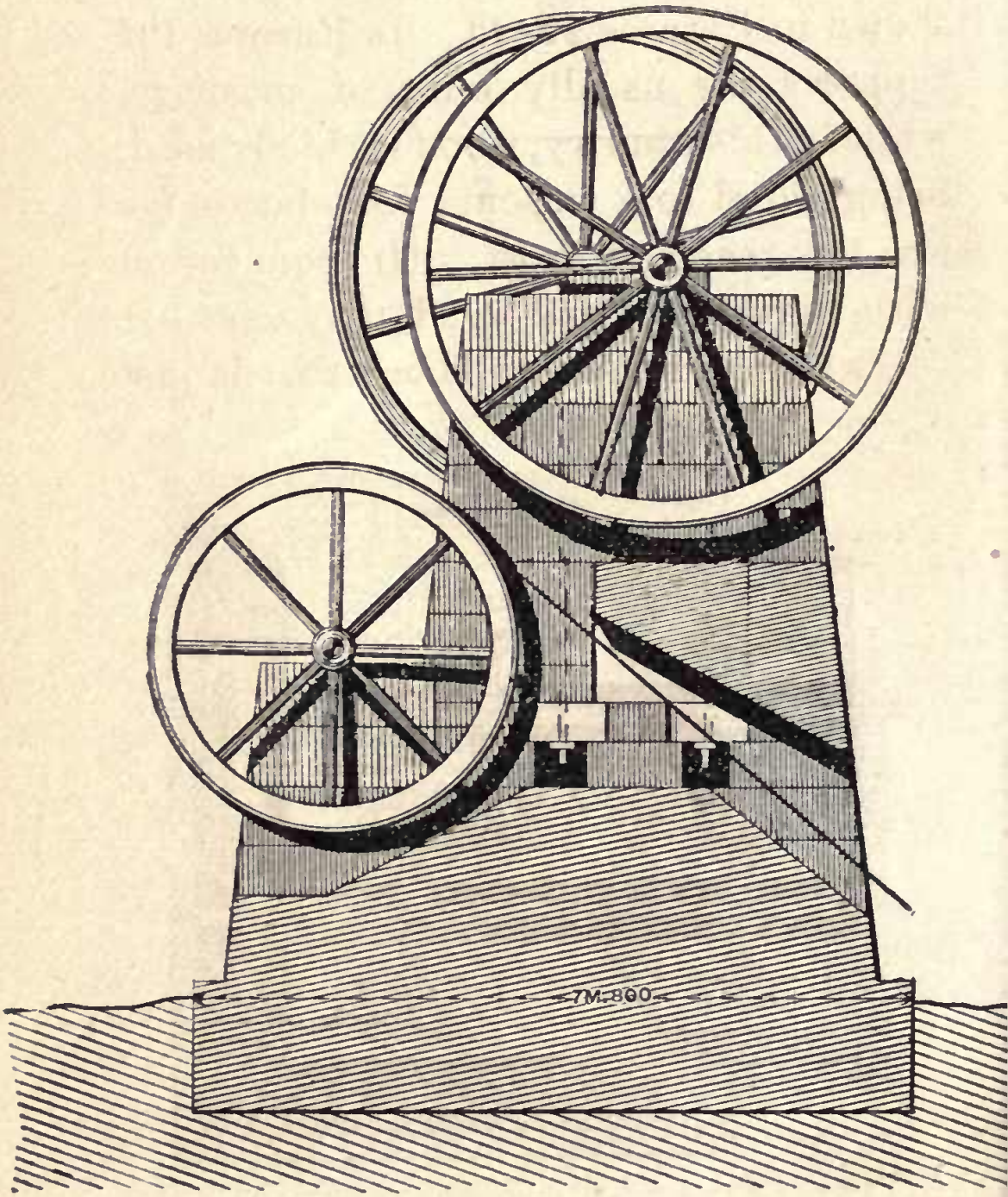
Fig. 21



transmitting any sudden movements of this kind.

The supports for the stations are various. They range in dimensions and

Fig 22



style from the simple wooden frame shown in Fig. 18, and the iron one of Fig. 19, to the more ornamental form of masonry (Figs. 20 and 21), and then to such immense masses of masonry as are shown in Figures 22–29. In Europe, the supports are usually built of masonry, while in this country, wood is chiefly used, beingbolted to a masonry foundation below the reach of frost. (In connection with Figures 20 and 21, I may say that the wheel there shown is one that is just

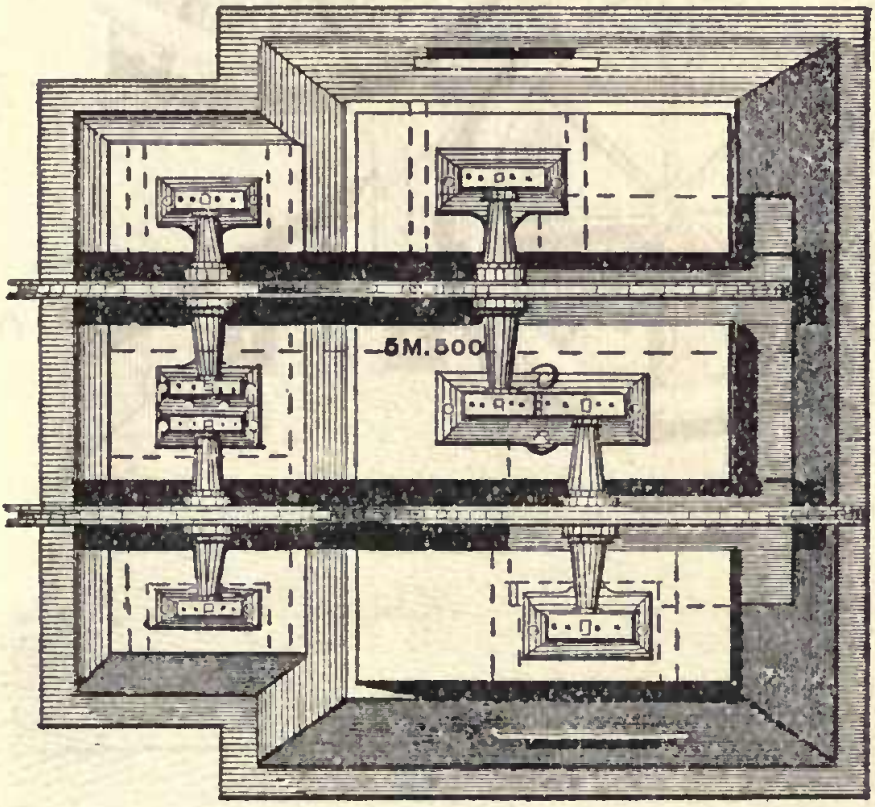
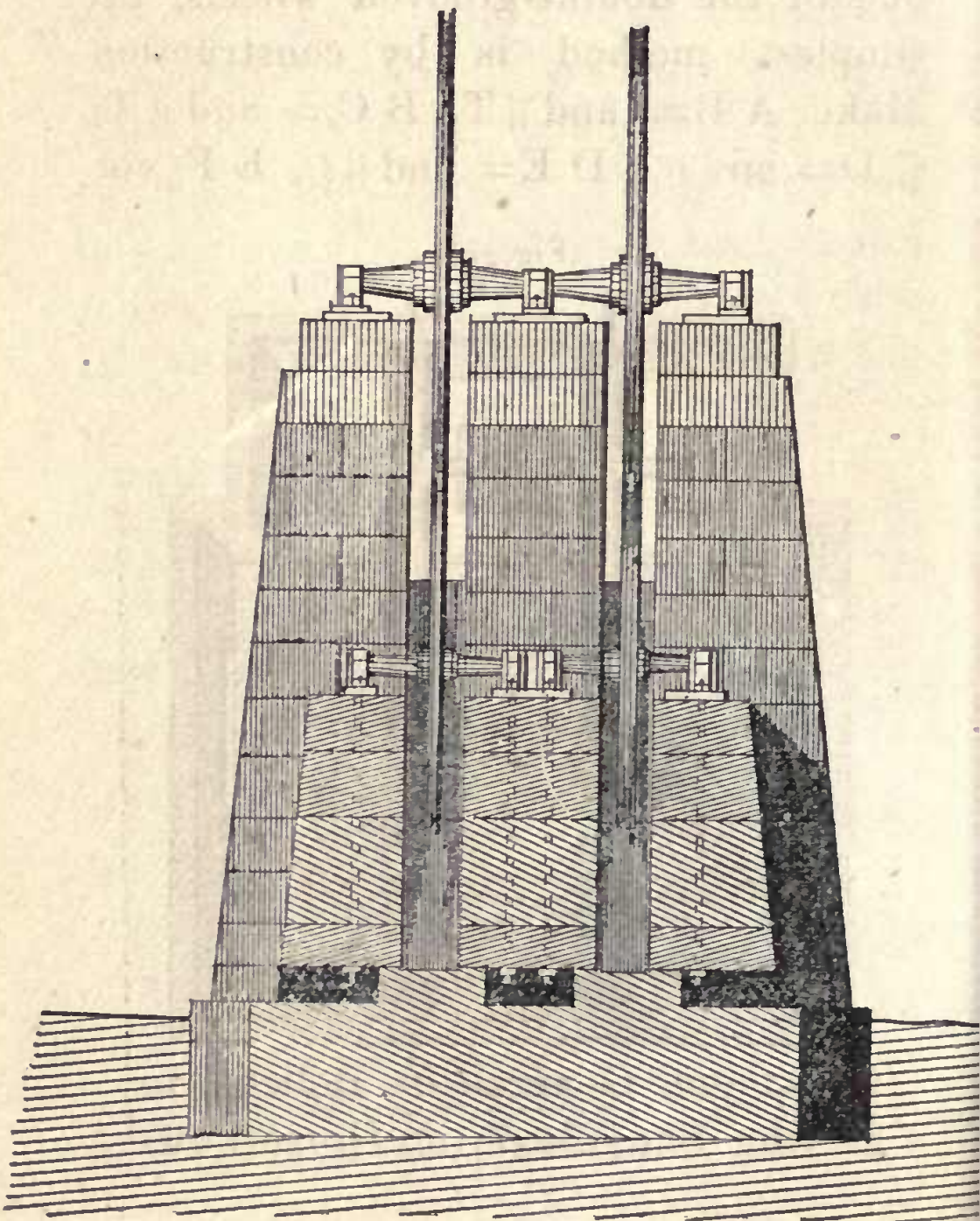


Fig 23

coming into use. It consists of a cast iron hub and a rim, which are united by sixteen tension rods.) When a wooden frame is made to support the wheel, it

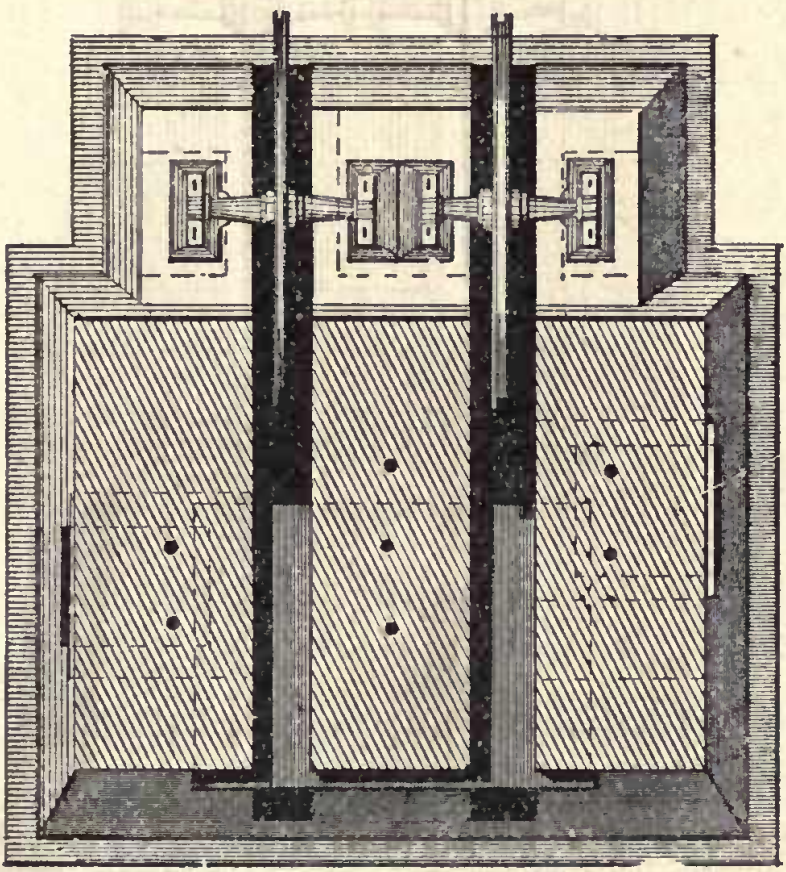
Fig. 24.



must be firmly braced side-ways, to keep the wheel in the proper plane, but end-bracing is not required, as there is no tendency to push it in either direction.

To find the pressure on the bearings of one of the double-grooved wheels, the simplest method is by construction. Make A B= and || T, B C_1= and || T_1, C D= and || t, D E= and || t_1, E F ver-

Fig. 25



Compagnie Générale de Bellegarde.
Carrying Sheaves (3,150 Horse-Power).

tical and = the weight of the pulley and shaft, then the line connecting A and E is the intensity and direction of the resulting pressure. (See Figures 30 and 31.) When the rope is put on the wheels, it is best to use an arrangement similar to that shown in Figures 32 and 33. It is bolted to the rim of the wheel as shown.

If it is required to change the direction of the rope at some station, it can be done by the interpolation of horizontal sheaves, or by connecting the vertical driving wheels by bevel-gear. The latter is more usually employed. (See Figures 34 and 35.)

Section IX.

SPECIAL CASES.

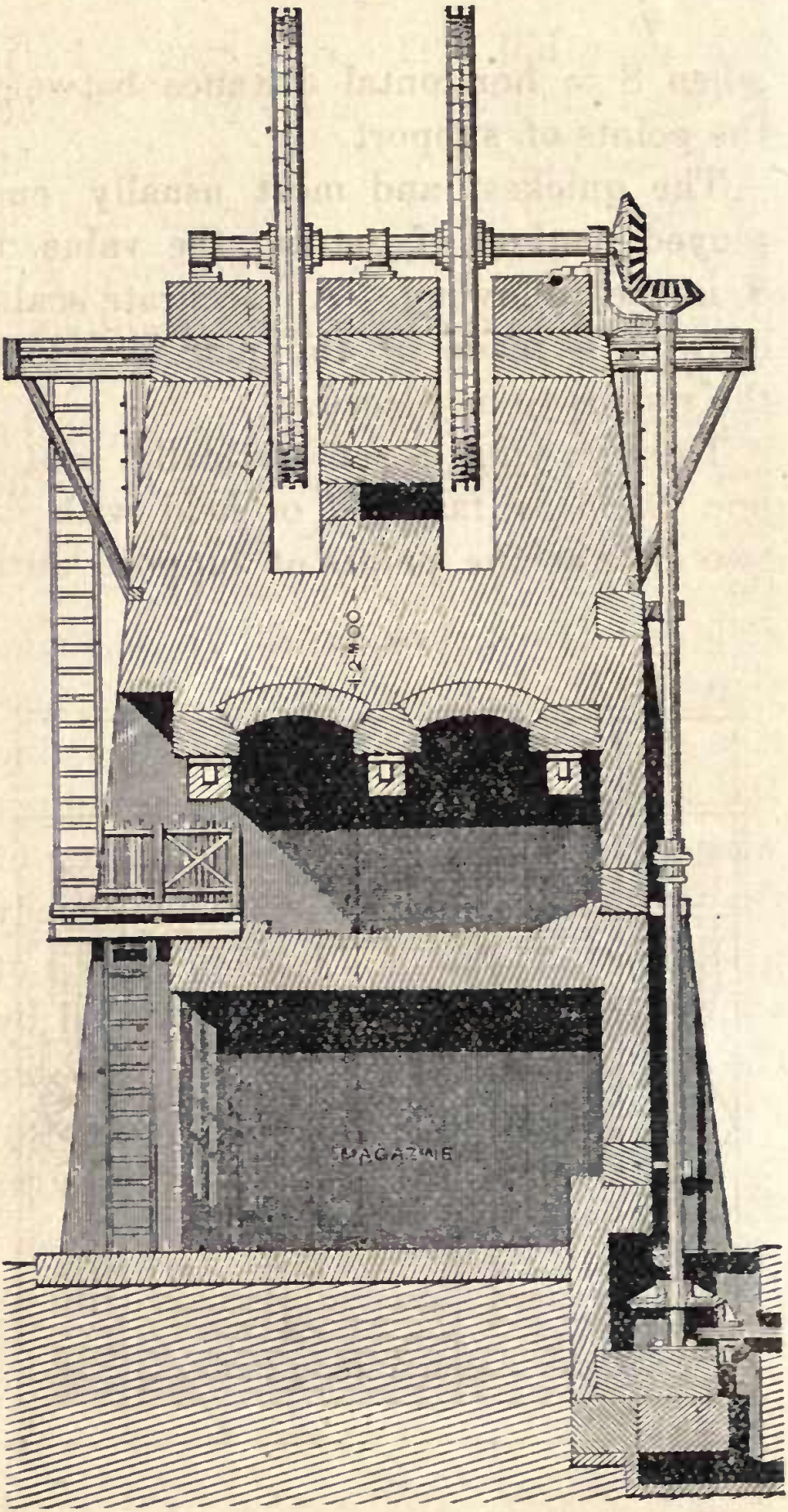
It sometimes happens, that the two wheels are not at the same height, as has been hitherto supposed, but that one is at a higher level than the other. This frequently happens where it is desired to use the power of waterfalls in a ravine, or in conducting power up or down the

side of a hill. The rope then takes a position similar to that shown in Fig. 36.

If the difference in height is slight, we can make use of the formulæ already found, without any serious error. But if it is great, we must take a different way, for in this case the tensions at the points of support are not the same, the lower one having a less tension than the one above. This somewhat complicates the problem, causing us to proceed as follows: We first make all the calculations for the lower wheel with the deflection Δ_1 and the span $2S_1$; we then find the tension in the rope at the upper wheel, and proportion the diameter of the latter according to rules previously given, so that the total tension shall not exceed the ultimate strength divided by the factor of safety. To do this we must first determine S_1; this can easily be done from the property of the parabola that

$$S_1 = S \frac{\sqrt{\Delta_1}}{\sqrt{\Delta_1} + \sqrt{\Delta_2}}$$

Fig.26



when S = horizontal distance between the points of support.

The quickest and most usually employed method of getting the value of S_t is the following. An accurate scale-drawing is made of the plan in which the rope is to be placed.

This drawing is set vertically, and a fine chain is fastened or held with its two ends at the points of support, until

Fig. 27.

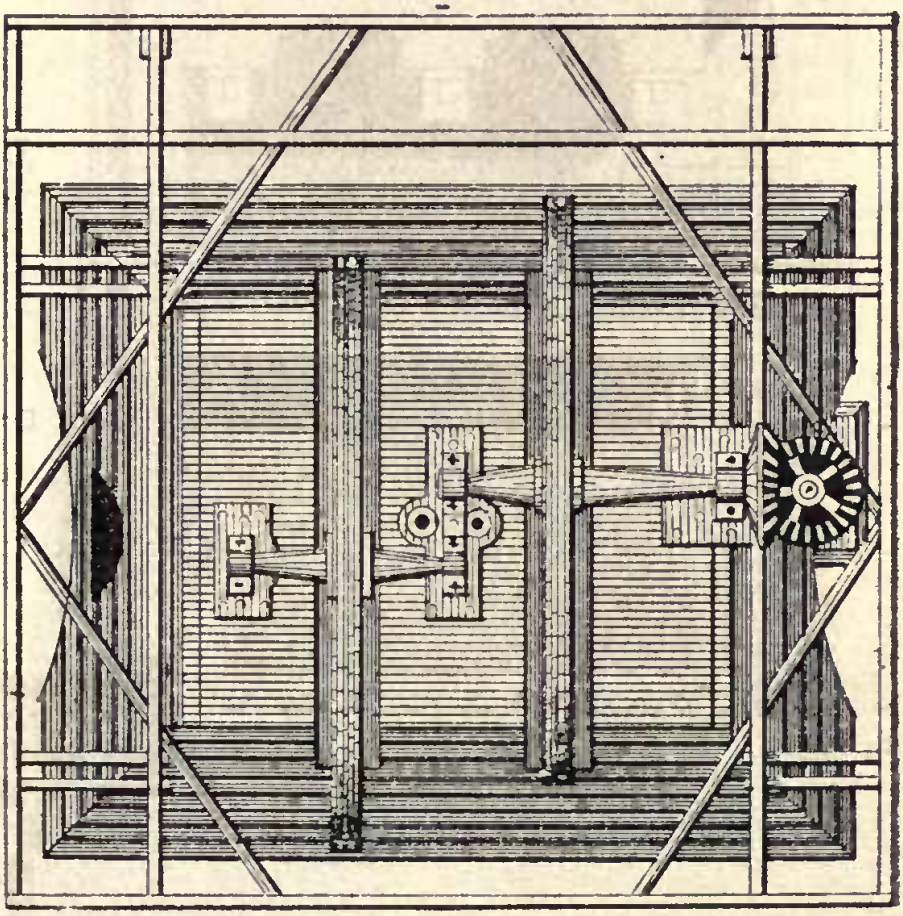
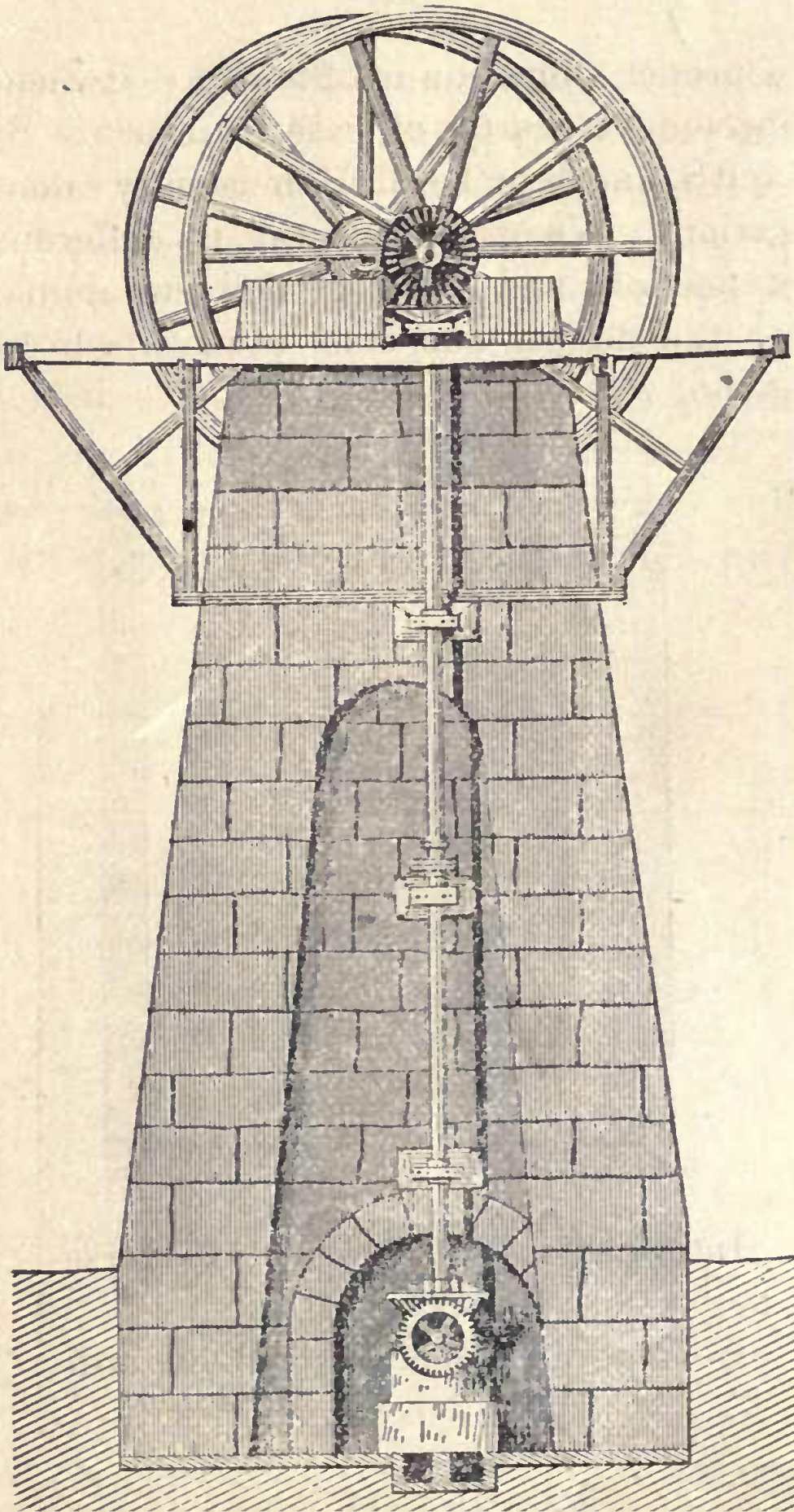
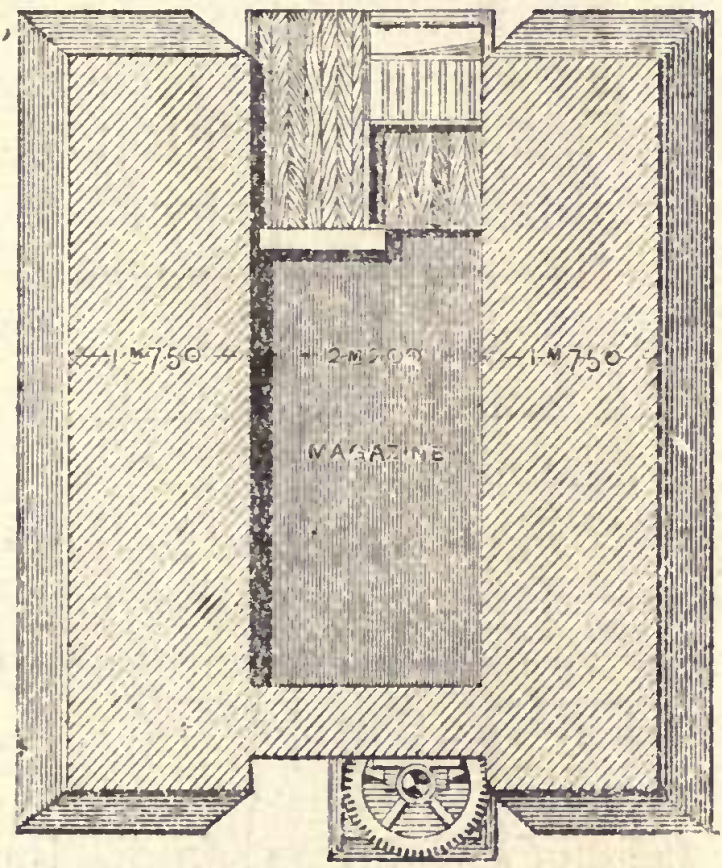


Fig. 28.



a proper deflection is obtained. It then becomes a matter of ease to measure S_1 and S_2, and to make all the necessary calculations. We can, in this way, try different deflections and observe their suitability to the design, but must always bear in mind, whether we are getting the deflec-

Fig. 29



Intermediate Station (3,150 Horse-Power).
Compagnie Générale de Bellegarde.
(See *Engineer*, vol. 37, 1874.)

tion of the driving or of the following side or that of both sides at rest. This method, though not giving as great accuracy as the solution of the above equation, is nevertheless largely used in practice, owing to its great convenience. It may be used when the pulleys are on the same level, showing between what limits we can work.

Another peculiar case is when the rope rises nearly in a vertical direction. This is the limiting case of the inclined transmission. The rope produces no tension whatever on the lower wheel, while at the upper wheel the tension is only equal to the weight of the rope. Even this last tension is such a small quantity as to be left entirely out of consideration, and we are consequently obliged to use some device for producing the requisite tension. Figures 37, 38 and 39 show various ways of accomplishing this object by means of tightening sheaves. In Fig. 38, as the rope passes around the wheel twice, the same must be provided with two grooves. Instead of

these tightening sheaves, we may, when practicable, put up two carrying sheaves as shown in Fig. 39, so as to have horizontal stretch enough to obtain the tension necessary.

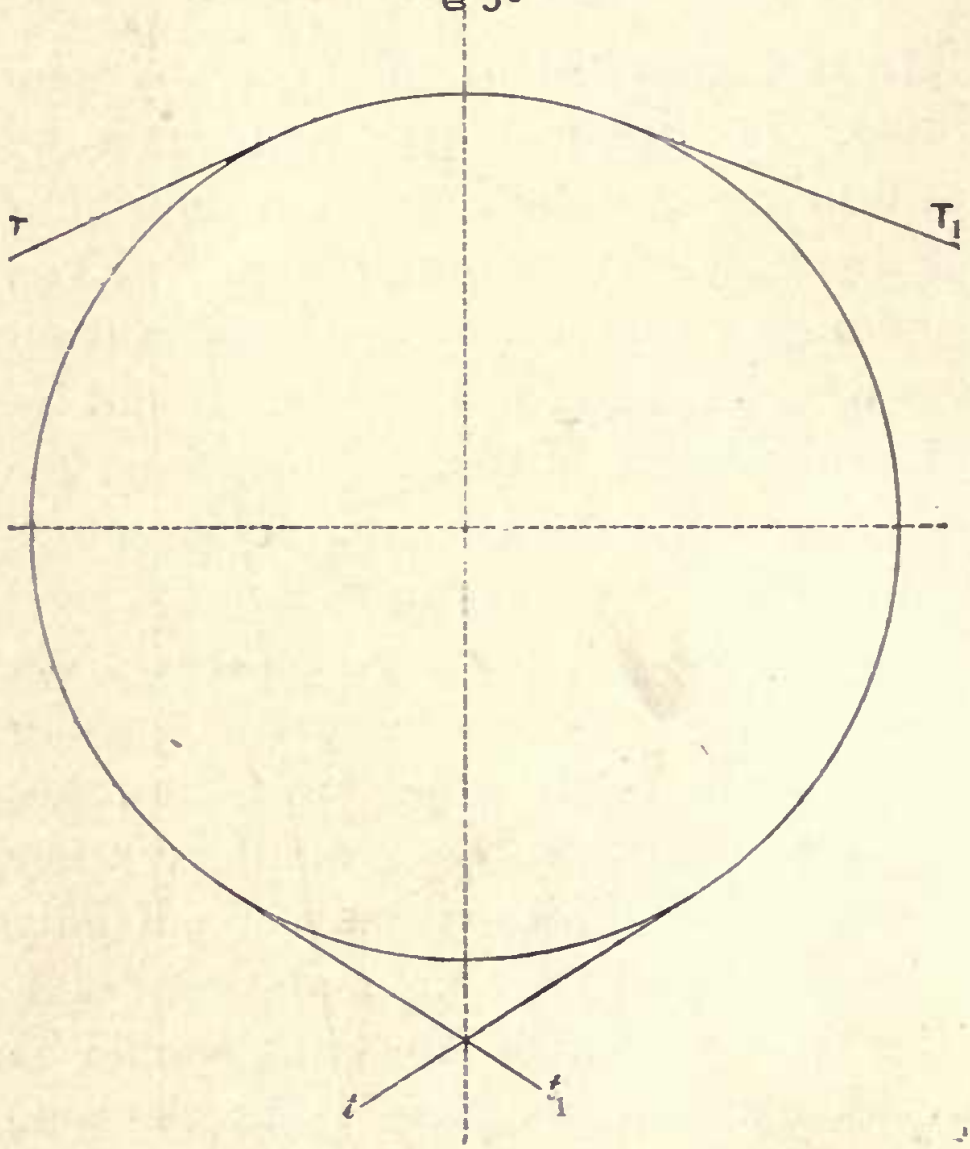
Section X.

Practical difficulties.

In the transmission of power by wire ropes, the greatest attention must be paid to keeping the ropes and the lining of the wheels in thorough repair. Even when the ropes are exceedingly taut on the wheel at first, it has been found by experience that, after a short time, the ropes stretch considerably. This causes the ropes, particularly in summer, to sag so much as to incapacitate them from transmitting the whole force, causing them to slip on the wheels; or the ropes begin to drag on the ground or other obstructions. This evil may be partially remedied by shortening and again splicing the rope, which, however, should be avoided as long as possible, as the rope

is ruined more rapidly by several re-splicings, than by long running under the regular working tension. I must remark that a wire rope stretches more as the wires make a greater angle with the axis of the rope; but as a rope having its wires parallel to the axis would

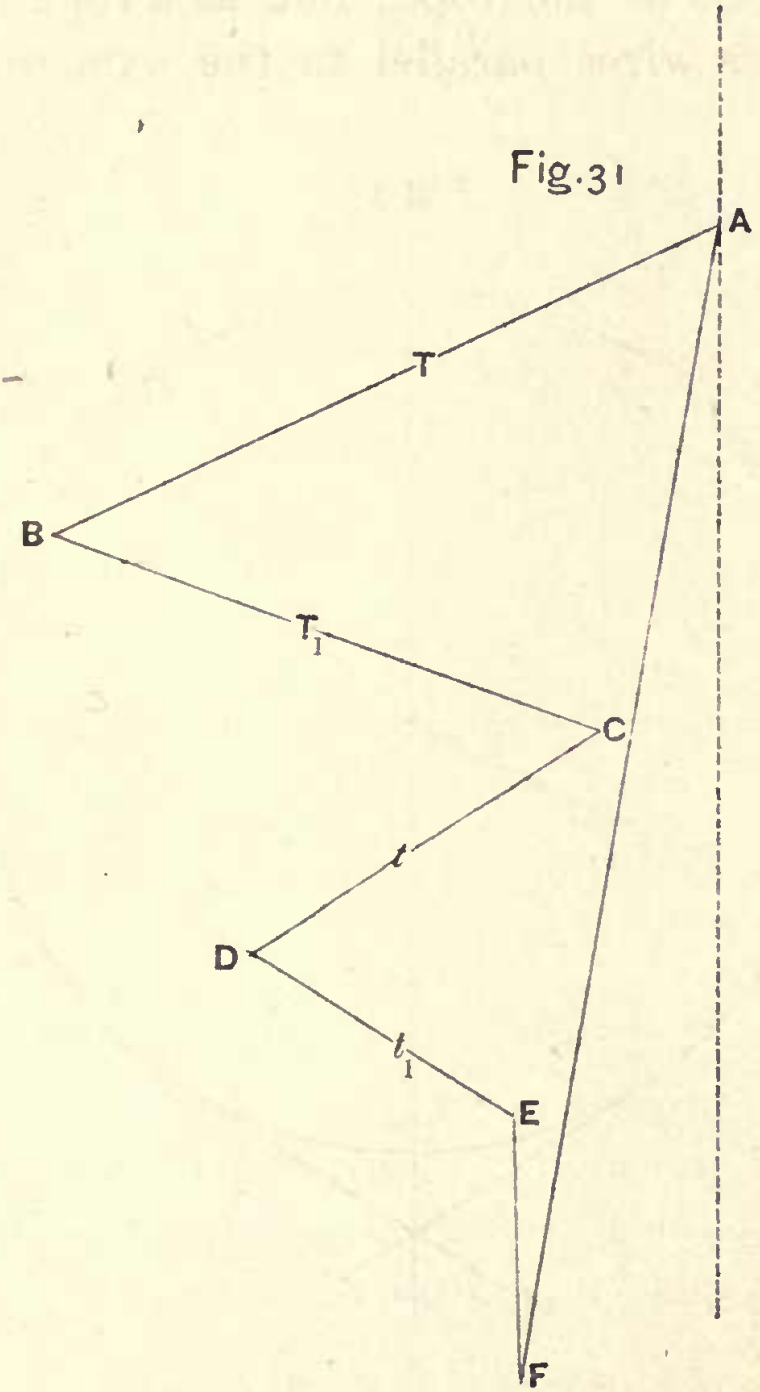
Fig.30



be useless, we must strive to keep the angle at its minimum value.

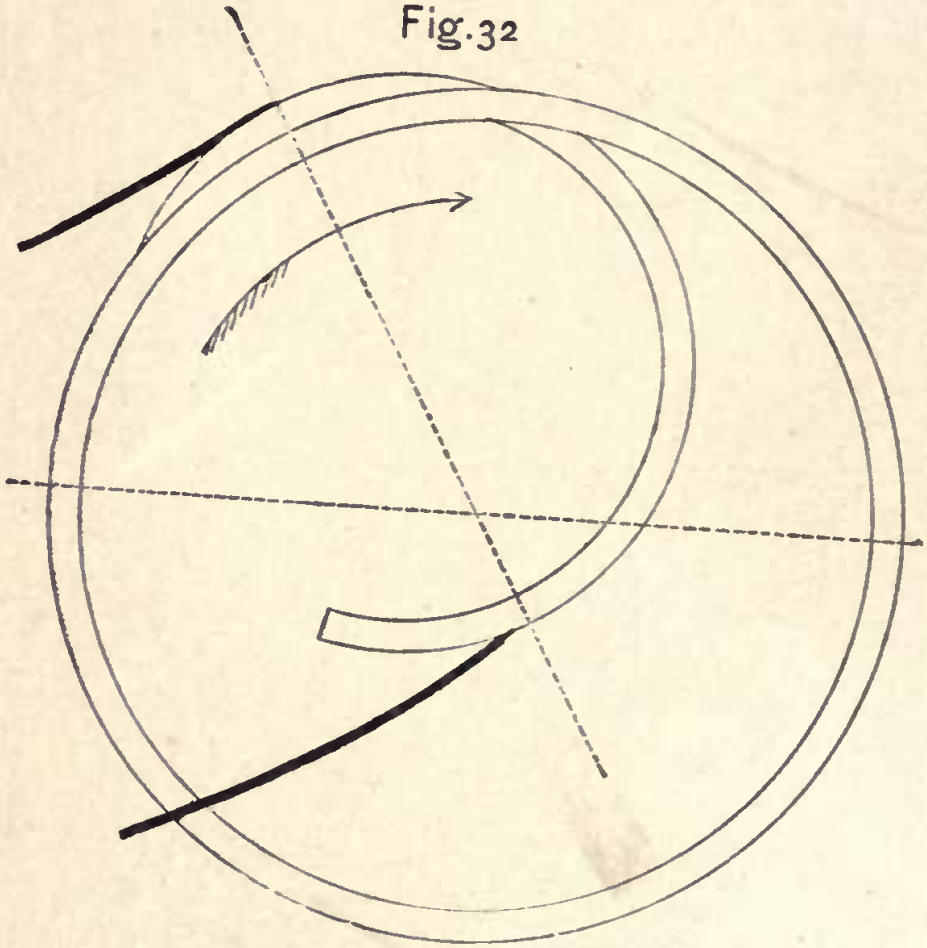
Experiments made with a view to stretching the ropes before putting them into use have not been very successful.

Fig. 31



It is only lately that the problem has been partially solved by a method of compressing the ropes while subjecting them, at the same time, to a great tensional strain. Wire ropes with wire

Fig.32



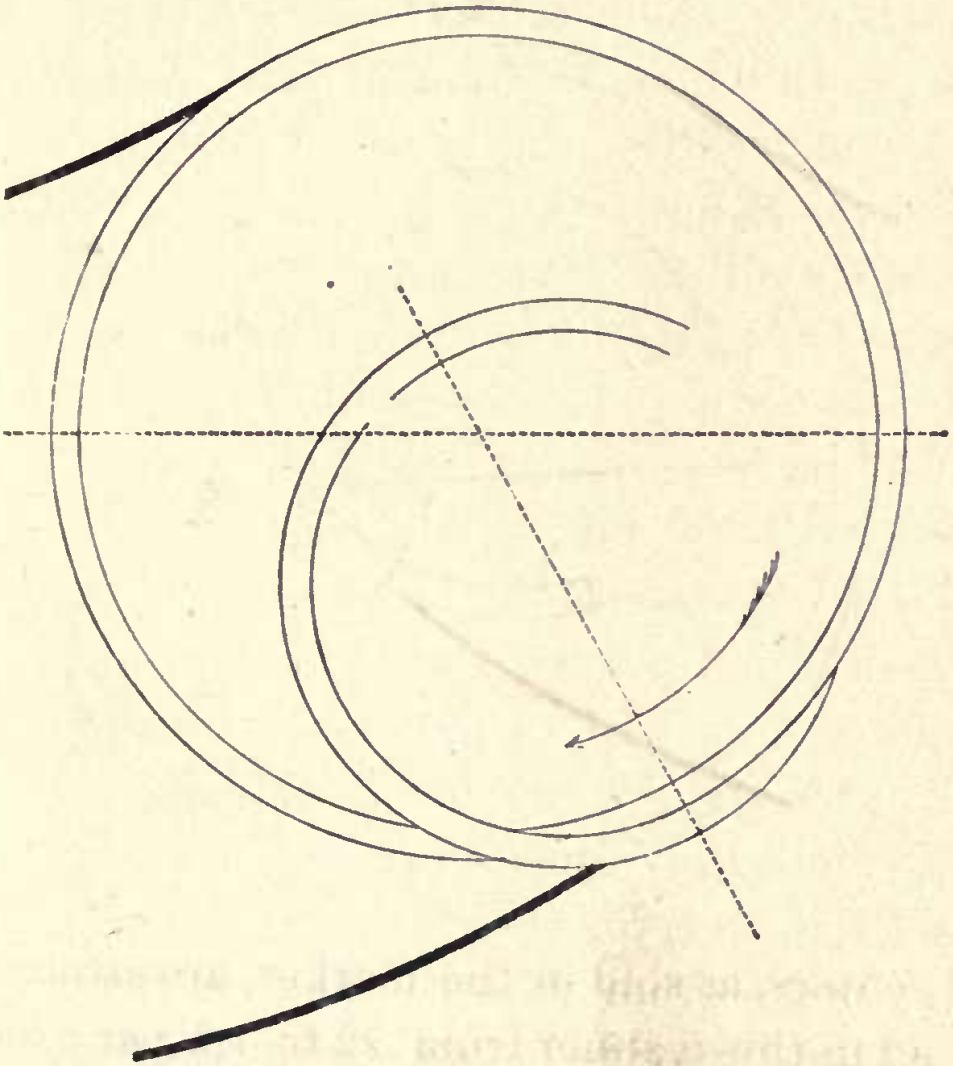
centers, as sold in the market, are stretched in this manner from .22 to 1.2 per cent.

Wire ropes with hemp centers, as generally employed for the transmission of power, are stretched from .71 to 2.6

per cent. of their original length, without at all impairing their strength.

Although this is a great step in advance, reducing the stretching of the

Fig. 33



rope, with its accompanying disturbances, to a minimum, yet even this is not sufficient to maintain a constant ten-

sion and deflection in the rope, and we are often compelled to use other means to restore to the same its original tension.

The simplest and most effective way of attaining this end is by re-filling the rims of the wheels, *i.e.*, by increasing their respective diameters to the proper amount, which is done in the following manner. (See Figs. 40–43.) Fig. 40 shows the cross section of a wheel with leather filling, and Fig. 41 the same wheel with its diameter enlarged by the superposition of the new filling, which is best made of poplar or willow-wood. It is made by taking straight pieces of about $1\frac{1}{4}$ inches in thickness, planing them into the necessary shape to fit the rim of the wheel, or merely cutting them into that shape by means of a circular saw, and providing their upper surfaces with grooves for the ropes. These pieces are made from 45–70 inches in length, and are provided on their insides with saw cuts going half-way through the wood. When we wish to put on this filling, the pieces are steeped in water

for a day or two, to render them more flexible. They are then nailed to the leather filling by means of suitable wrought nails, which should be somewhat longer than the thickness of both fillings together, so that after passing through the leather they may strike the iron below and be clinched, thus affording a better hold. The nails must be driven as shown in Figs. 41 and 42, and especial care must be taken that there are no projecting ends within reach of the rope. The whole operation can easily be performed in an hour, without throwing off the rope. In case the filling of one wheel in this manner is not sufficient to accomplish the desired result, we perform the same operation on the other wheel. If this is still insufficient, the whole process is repeated with a second layer. When the rope has finally become of a constant length, which usually takes place in the course of a year, we may carefully remove all but the leather filling, and then shorten the rope to the proper length, allowing

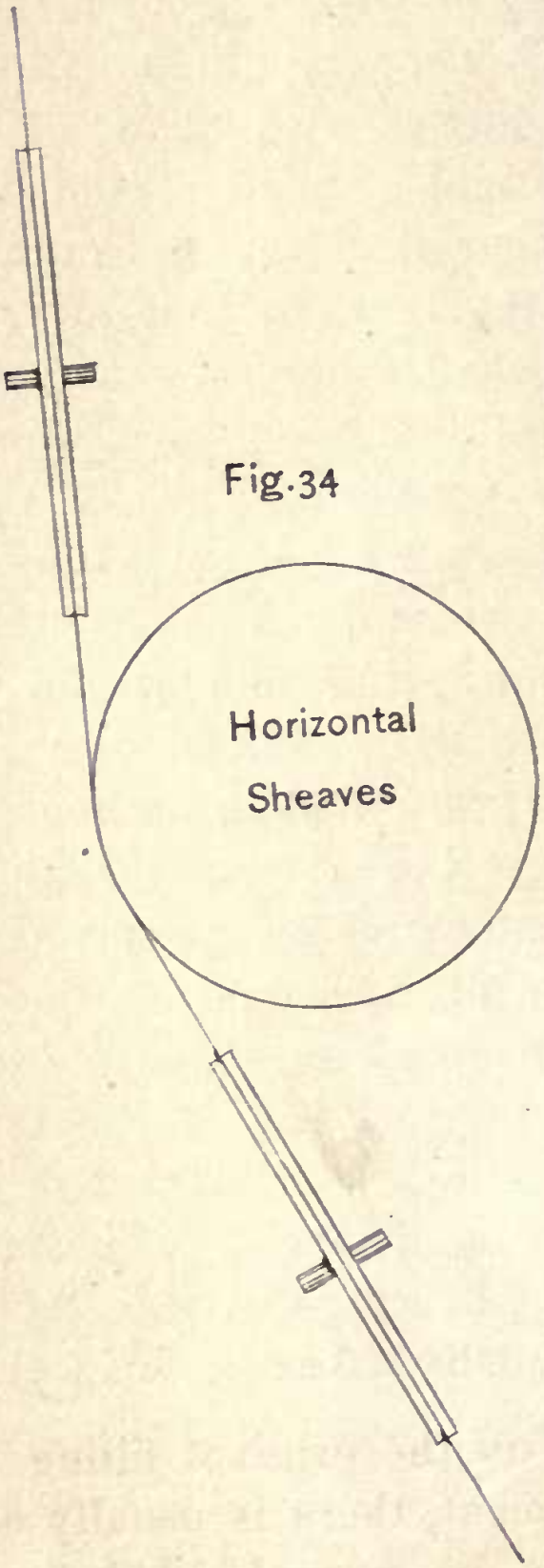
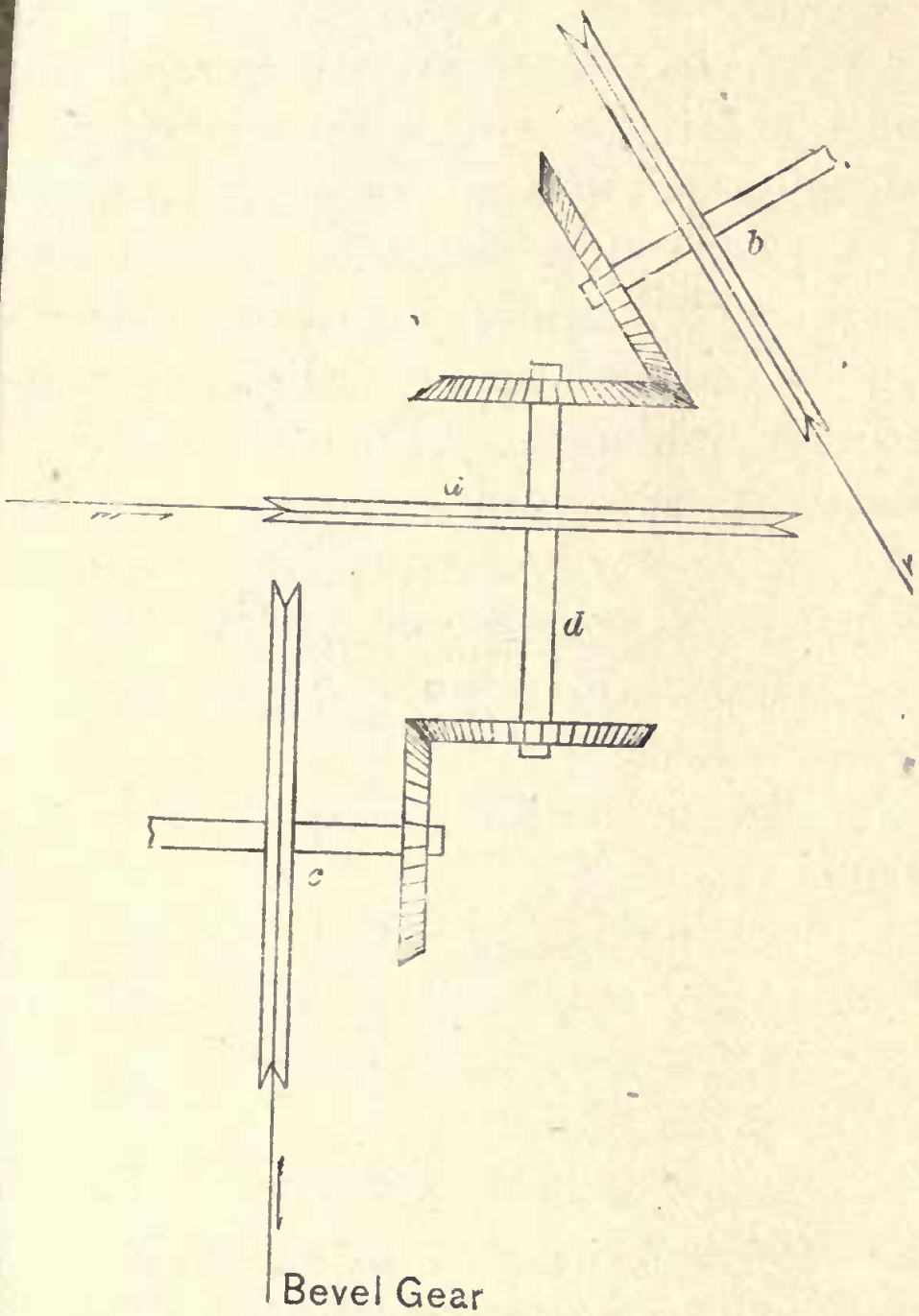


Fig.34

Fig. 35



it to run on the original filling. After this treatment, there is usually no more trouble to be apprehended from this

source, but there are some other difficulties which must be guarded against.

When the transmission is in good running order, the ropes should run very steadily and without swaying laterally. If the latter does occur, it is due to one or more of the following causes, (leaving out of consideration the slight swaying motion produced by the wind, or by an excessive velocity);

1. When the wheels are not perfectly balanced or are not true circles.

2. When the wheels are not in the proper plane.

3. When the filling is in bad condition.

4. When the rope is too much worn.

5. If the rope has been badly spliced.

6. If the rope touches the ground or other obstructions.

1/ It is absolutely necessary to balance the wheels perfectly; as, if they are not well balanced, the centrifugal force, at the velocity with which they are driven, exercises a very prejudicial effect on the bearings of the shaft, as well as on the

rope. The bearings wear out faster and waste more power in useless friction, while the rope begins to swing, sometimes to such an extent as to be thrown violently against the side of the wheel groove thus wearing out very rapidly.

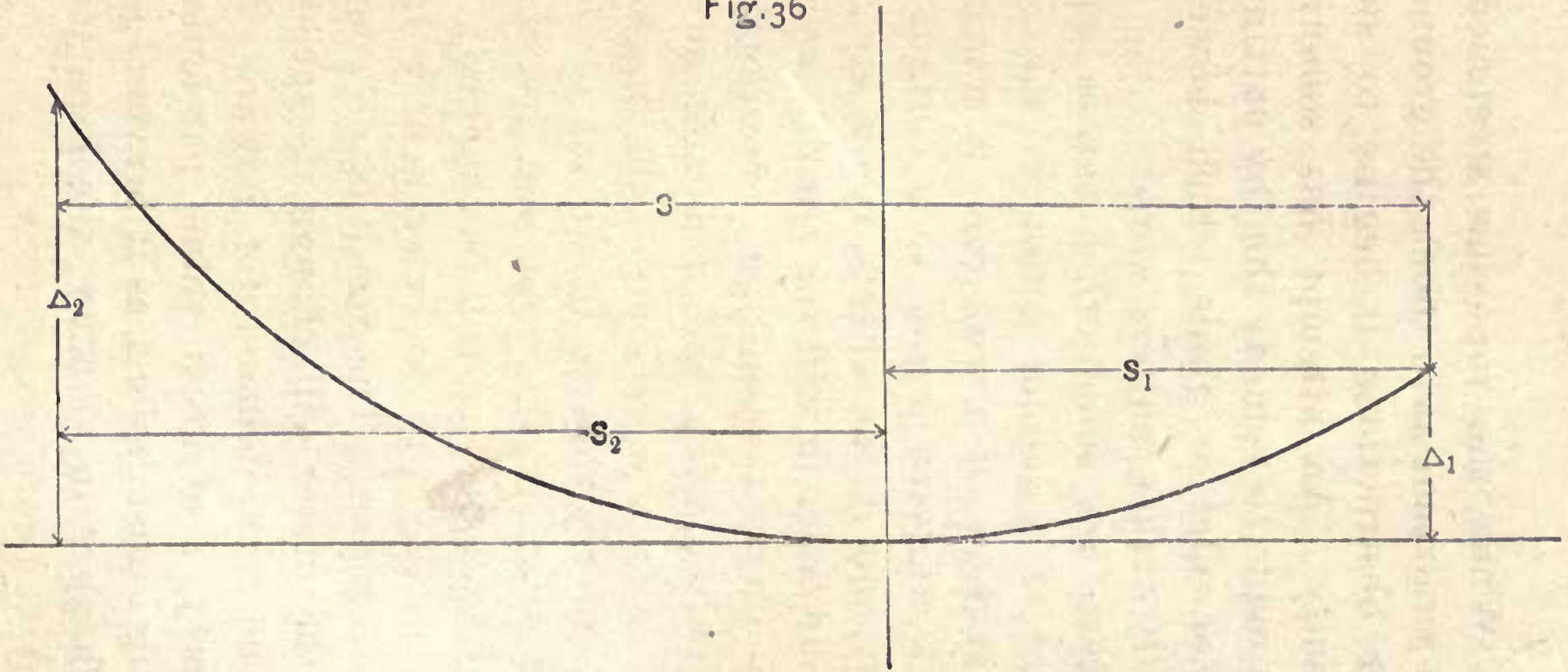
2/ In mounting a transmission, the greatest care should be taken to get the wheels in the same vertical plane, and the shafts perfectly horizontal, inasmuch as any deviation from this position immediately shows itself in the rope.

3/ In case the filling is in bad condition and worn unequally, it causes the rope to swing in a vertical plane. The remedy is to cut the filling so as to make it equally thick all around.

4/ If there are ends of wires projecting from the rope, then every time that one of these projections passes over the wheel, the rope receives a slight shock, causing it to swing. The same action takes place if torn or loose strands occur in the rope.

5/ If the rope has been badly spliced, or given a false turn, it will not run steadily.

Fig.36



6/ When the rope has stretched to such an extent as to touch the ground or other obstructions, it begins to swing violently. An attempt has sometimes been made to remedy this by putting in a little roller or guide, which, however, usually makes matters worse.

There are some other causes which induce an irregular action in the rope. For instance, if a wire rope is transmitting a constant power to a certain distance, and if the wheels, ropes, etc., are in good order, it will run steadily as long as the power transmitted corresponds to a certain tension and deflection in the rope. But now, if some of the machines are suddenly thrown in or out of gear, the tension in the rope and its corresponding deflection will be changed, thus causing the rope to sway gently in a vertical plane. The result is, of course, that the motor will change its speed to suit the new demand for power. This property is of great value, particularly in long transmissions, as it prevents sudden changes in velocity, the rope itself acting as a sort of governor.

Another cause of swinging is found in very powerful transmissions, where it becomes necessary to use two ropes to transmit the power, connecting the two wheels by a differential gear. The object of this gear is to equalize the tension

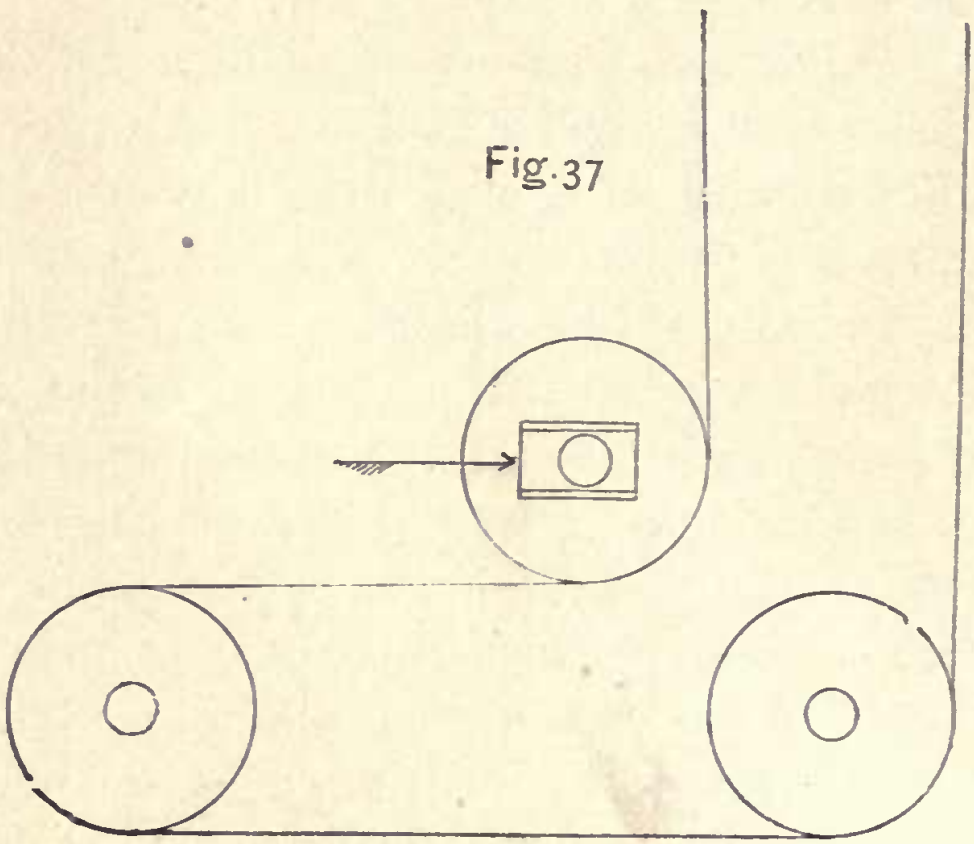
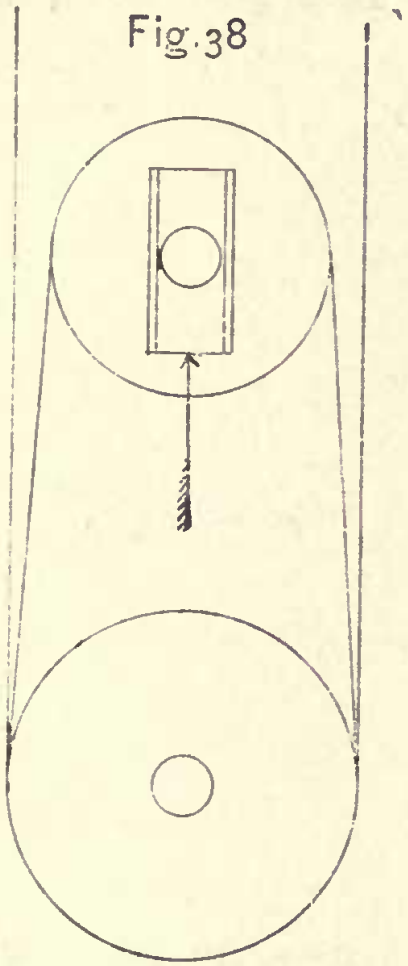


Fig. 37

in the two ropes, as neither this nor the diameter of the wheel can be exactly maintained in two wheels running side by side. As the cross-head of the differential gear is firmly connected with the shaft, while the wheels with their bevel-

gear run loose on the same, the result is that when the tensions or the effective diameters of the wheels are not the same in both, there is an additional rotation of one or the other, caused by the differ-

Fig. 38



ential gear. This produces slight vertical oscillations, which, however, have no prejudicial influence on the working of the ropes.

Wire ropes are sometimes used to

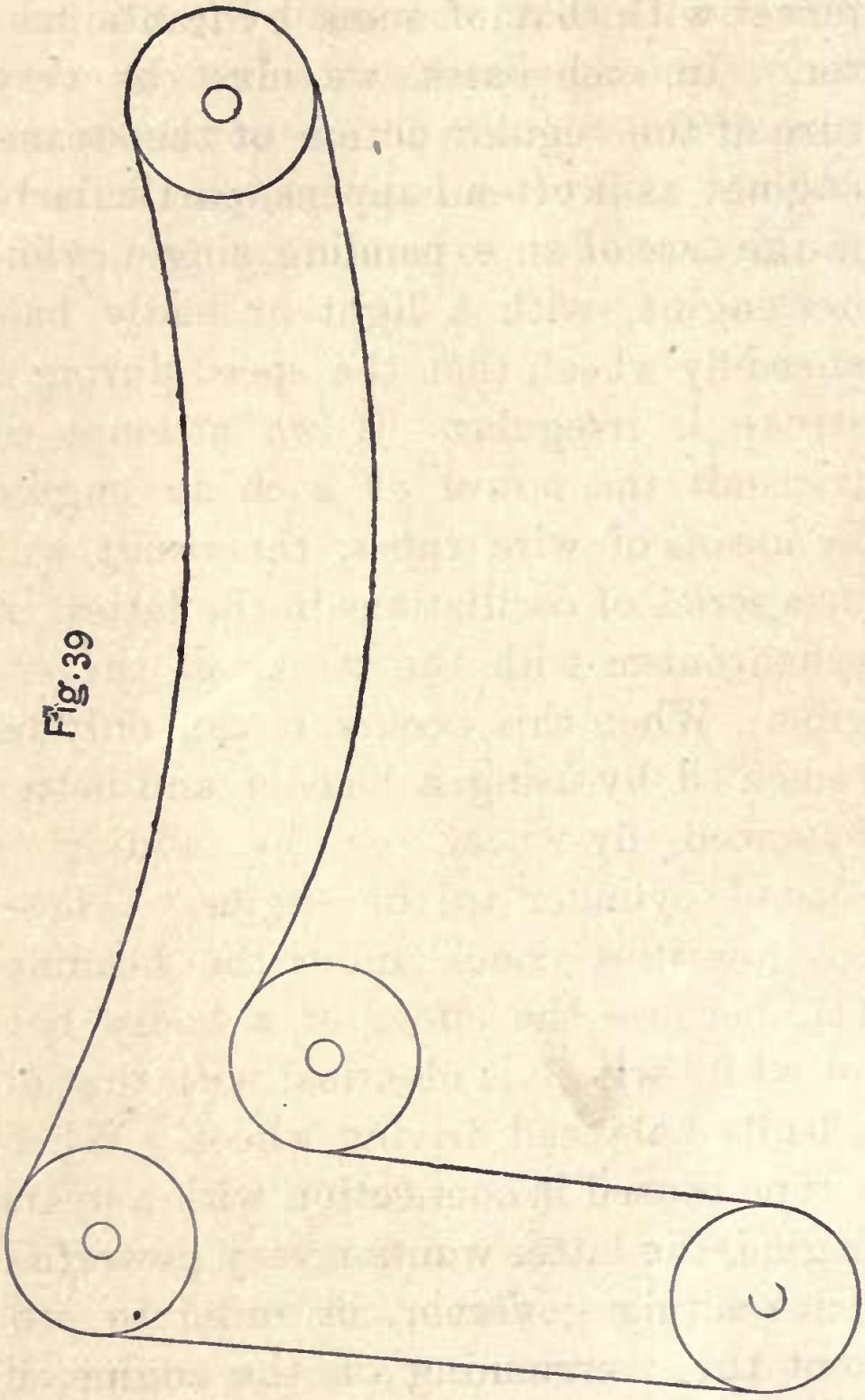


Fig. 39

transmit the power of a steam-engine to a distant building, or to combine its

power with that of some hydraulic motor. In such cases, we must be very sure of the regular action of the steam-engine; as it often happens, particularly in the case of an expanding, single cylinder engine, with a light or badly balanced fly-wheel, that the speed during a stroke is irregular. If we attempt to transmit the power of such an engine by means of wire ropes, the result will be a series of oscillations in the latter, in synchronism with the stroke of the engine. When this occurs, it can only be remedied by using a heavier and better balanced fly-wheel, or by adding a second cylinder to the engine. These irregularities come under the heading (1), because the effect of a badly balanced fly-wheel, is identical with that of a badly balanced driving wheel. When a rope is used in connection with a steam engine, the latter wants a very powerful, quick-acting governor, in order to prevent the overrunning of the engine, if the rope should suddenly break. Such an accident happened a few years ago in

a cotton spinning establishment in Alsace, causing the complete destruction of a large steam engine.

Fig. 40

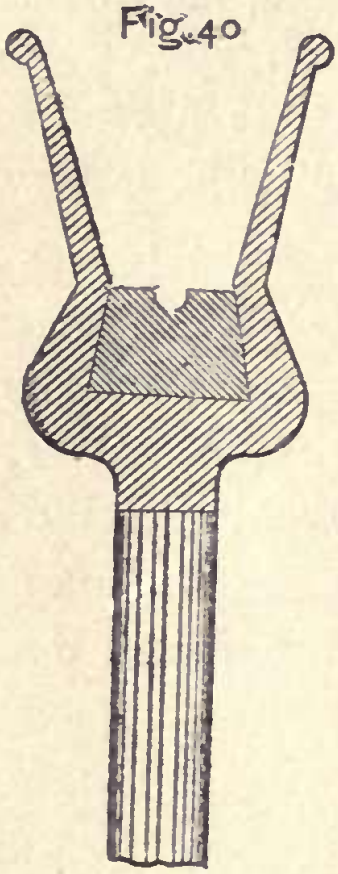
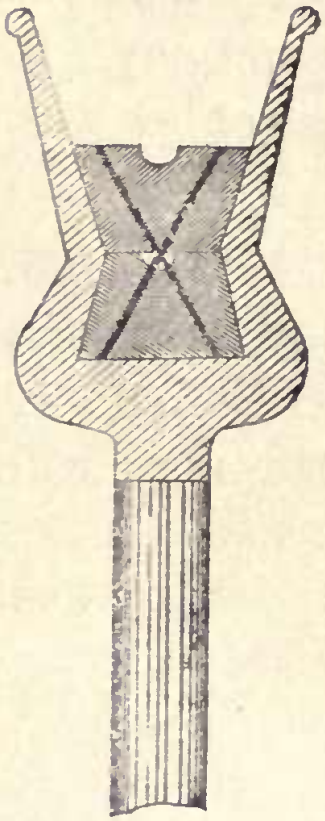


Fig. 41



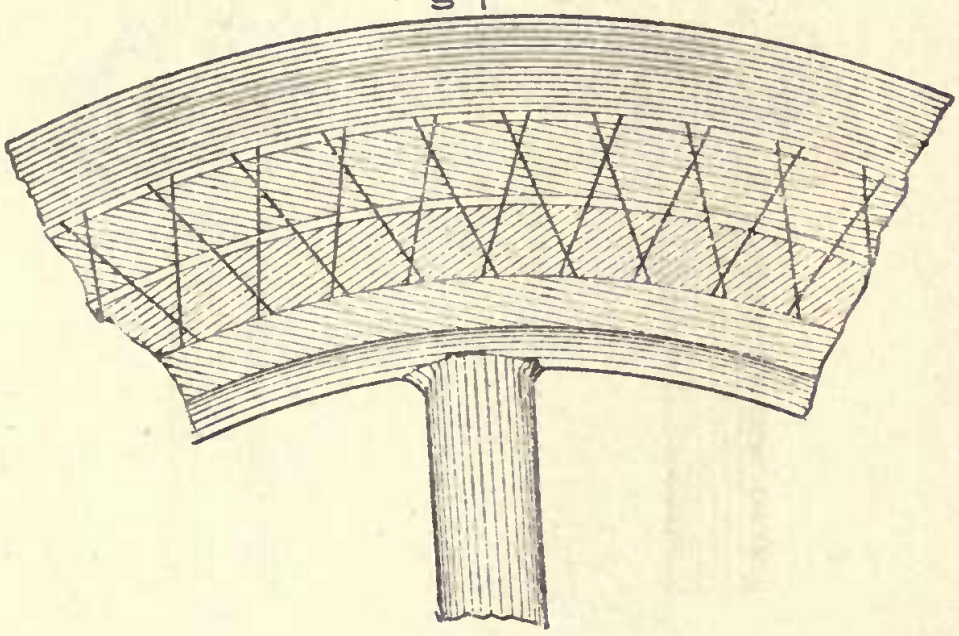
Section XI.

FILLING FOR THE WHEELS.

The filling first employed by Mr. A. Hirn, consisted of a strong leather belt, covering the whole rim and fastened to the same by wooden wedges. With wheels of large diameter, he was obliged to make this belt of several pieces,

thereby weakening it considerably. This style of filling, however, rarely lasted longer than a few months. Hirn was then induced to try rubber, which has remained in considerable use up to the present day. But with very large wheels, the rubber was found to be unsuitable

Fig 42



for the following reasons: Rubber expands greatly with heat, and when wheels filled with it are exposed to the direct and strong rays of the sun, the rubber becomes soft and is cut by the rope, or it expands over the edge of the wheel, causing the rope to be thrown off. In some cases, where the filling expanded

Fig. 43

greatly at noon, it returned to its original position during the night. On the

other hand, there are cases known, when in cold nights during the stoppage of the transmission, the rope would freeze to the rubber filling. On starting in the morning, large fragments of the brittle rubber were torn out. Besides this, rubber is also slowly dissolved by the oil and grease on the rope.

After some unsuccessful attempts at filling with hippopotamus skin, willow and poplar wood were tried, giving quite passable results. Strips of poplar wood about $\frac{7}{8}$ inch thick and seven to ten feet long were planed to the proper section, softened in hot water, and then driven in without any special fastening. This process was very simple, allowing the wheels to be re-filled quickly and at slight expense. The main difficulty was that the filling sometimes became loose, owing to the drying and shrinking of the wood during the hot season. This was partly prevented by driving pieces of wire through the filling and the rim of the wheel. The wood was also softened in hot glycerine instead of hot water,

thus rendering it less subject to the action of the air. In spite of these precautions, a wooden filling rarely lasted more than six or nine months, when the wood was most carefully selected; while if knots or unsound spots were present in the filling, it wore out in a still shorter period. Various other woods were then tried, but willow and poplar were found to be the most durable as well as the cheapest. As wood wears less when subjected to strain and pressure across the direction of the grain, this method was also tried, notably at the immense Schaffhausen water works. In this case, small pieces were cut, having the fibre running from side to side of the rim of the wheel. These pieces were then dried thoroughly, and frequently immersed in linseed varnish until they were completely saturated with the latter, thus becoming more durable and air-tight. Notwithstanding these precautions, some of the pieces became loose, and, although more durable than the plain wood filling previously described, they did not last

longer than about one year. A further trial was made with wood filling, in which the fibres ran radially, but with no better results. But this last method has the advantage that when the rope wears a groove into the wood, the sides do not split off as easily as in the two other styles. Cork has also been tried to some extent, but it was found of little value to transmit any considerable force, as it wore out very rapidly.

Again, by wedging the groove full of tarred oakum, a cheap filling is obtained, nearly as good as leather, and not so tedious to insert.

Another plan is to revolve the wheel slowly, and let a lot of small sized ratlin or jute-yarns wind up on themselves in the groove; then secure the ends. After a day or two of running, the pressure of the rope, together with the tar, will have made the filling compact.

The first attempts with the radial leather filling were made about 1865; and it was soon found that this method of filling was so decidedly superior to all

others, that it has now come into almost exclusive use. It is easily inserted by any ordinary mechanic. The separate pieces of leather are driven hard against each other in the groove of the wheel. The key or closing piece is made of india-rubber, which is first softened in hot water and then driven into its proper place. The greatest wear of the filling occurs not, as might be expected, in the driving wheels, but in the carrying sheaves of an intermediate station, and there principally in the smaller pulley. This is due partly to the great speed, and partly to the fact that the perimetral velocity of the pulley is often greater than that of the rope itself.

The life of leather filling depends on the quality of leather used, and on the radial thickness of the pieces. It is also affected by the tension, and general condition of the ropes. It may usually be estimated at about three years.

Section XII.

EFFICIENCY.

The losses in the transmission of power

by wire ropes are caused by several resistances:

1. The rigidity of the wire ropes in circumflexure of the two main wheels, and through the change of angular direction at either side of the carrying sheaves.

2. Friction of shafts of the wheel.

3. Resistance of the air to the rotation of the wheels and to the passage of the rope through it.

The loss due to the rigidity of the ropes may be regarded as insensible; because when the diameters of the pulleys are sufficiently large, the wires of which the rope is made straighten themselves by their own elasticity after having been bent.

The losses due to the friction of the shafts, and the resistance of the air, have been determined theoretically and practically. Letting, as before, t' = working tension, t_0 = tension produced by bending, we have for the loss of power for the two main wheels, when

$\frac{t'}{t_0}$ =	$\frac{2}{7}$	$\frac{1}{2}$	$\frac{4}{5}$	$1\frac{1}{4}$	2	$3\frac{1}{2}$
loss=	.024	.025	.024	.022	.020	.016

The greatest loss .025 takes place when $\frac{t'}{t_0}=\frac{1}{2}$, as might have been expected; for we previously found this to be the condition for obtaining the smallest wheel. But even this maximum loss is a trifle. If we consider, that with favorable conditions, we can lead a wire rope from 500–900 feet without any intermediate support, while shafting of this length would cost an immense sum, besides being exceedingly inefficient, we can well appreciate the convenience and value of this method of transmitting power.

For the carrying sheaves the loss is as follows: when

$\frac{t'}{t_0}$ =	$\frac{2}{7}$	$\frac{1}{2}$	$\frac{4}{5}$	$1\frac{1}{2}$	2	$3\frac{1}{2}$
loss=	.0012	.0013	.0012	.0011	.0010	.0080

So that the efficiency in the most unfavorable circumstances, *i.e.* when $\frac{t'}{t_0}=\frac{1}{2}$, may be arrived at thus:

1. Overcoming the axle friction of the driving and following main-pulleys..... 0.250
2. Overcoming axle friction of each intermediate sheave..... .0013

Hence the efficiency is E=.975—.0013 N, where N is the number of carrying sheaves.

Section XIII.

ESTIMATES.

It is impossible to give any definite idea as to the cost of erecting and maintaining a transmission. In France, where by far the greater number of applications are made, the cost of the machinery and its erection is estimated at 5,000 francs per kilometer, exclusive of the necessary constructions at the termini, which are said to require an additional expenditure of twenty-five francs per horse power.

The average cost is about one-fifth that of belting, and about one-twenty-fifth that of shafting.

But the number of carrying sheaves,

distance, height of columns, etc., vary so exceedingly, that no more than a very vague idea can be given of the cost except by making an estimate for every special case. To make this a matter of ease, I have appended a list of the current prices of several articles, the first being the price of "Wheels bored to fit shaft and lined with rubber or leather":

Diameter.		Price.	
1½	feet.....	$6.00	each.
2	"	8.00	"
3	"	25.00	"
4	"	33.00	"
5	"	53.00	"
6	"	75.00	"
7	"	95.00	"
8	"	125.00	"
9	" cast in halves	225.00	"
10	"	300.00	"
11	"	350.00	"
12	"	400.00	"

Special prices for larger wheels.

When the lining is worn out in these wheels, new filling, either of rubber or leather may be bought at 60 cents per pound.

The price of the ropes will be found in the wire-rope table previously given.

Section XIV.

HISTORICAL SKETCH.

The first transmission was put up by the brothers Hirn in 1850, at a calico weaving establishment, near Colmar. An immense mass of scattered buildings seemed to forbid the possibility of using them, and yet placing the motive-power at any one point. In this emergency, they first tried this method of force transmission, using a riveted steel ribbon to each building from the engine-house. The steel bands were about $2\frac{1}{2}$ inches wide by $\frac{1}{6}$ of an inch thick, and ran on wood-faced drums. This presented two inconveniences. In the first place, on account of its considerable surface, the band was liable to be agitated by the wind; and secondly, it soon became worn and injured at the points where it was riveted. It served, however, very well for eighteen months to transmit twelve horse-power to a distance of eighty meters.—The success of the principle was complete, but much remained

to be done before the wire rope and the rubber or leather-lined driving wheel solved all difficulty, and brought the principle to be a practical reality.

The number of applications of this method of transmitting power has increased very rapidly. At the end of 1859, there were but few applications in use. In 1862, there are known to have been about 400, and in 1867 about 800. At the present time there are several thousand in successful operation. In 1864, a terrible explosion destroyed almost all of the great powder mill at Ockhta, situated about six miles from St. Petersburg. The whole establishment was rebuilt. After studying many combinations, an artillery officer proposed to profit by the resources which the telodynamic cables offered to engineers, and thus to realize the only combination which could prove successful in a powder-mill; namely, a great distance between the buildings, so that the explosion of one should not entail the ruin of the rest. The new establishment, which

went into operation in 1867, is composed of thirty-four different workshops or laboratories, to which motive power is transmitted by means of wire ropes driven by three turbines, thus distributing a total of 274 horse-power along a line nearly a mile in length.

The largest transmission is that employed to utilize the falls of the Rhine, near Schaffhausen, in Switzerland. Advantage was taken of the rapids at one side, to put in a number of turbines, aggregating in all 600 horse-power. Since the steep rocky banks forbade the erection of any factories in the immediate vicinity, the entire power was transferred diagonally across the stream to the town, about a mile further down, and there distributed, certain rocks in the water being made use of to set up the required intermediate stations. In the industries we frequently meet with a similar case. Many valuable sites for water-power are lying idle in this country, for want of building room in their immediate vicinity. New England espe-

cially abounds with them. Coal being so dear there, their value is all the greater. Since the water can only be led down hill in certain directions, the cost of a canal or flume would in most cases come too high, and so the power remains unimproved. By ropes, however, we can convey the power of a turbine or water-wheel in any direction, both up stream and down stream; up an ascent of 1 in 8 or 10, or down a moderate slope as well. The power need not be confined to one factory, but may be distributed among a dozen, if necessary, located so as to suit their particular business, and not to suit the oftentimes inconvenient location of a canal.

Thus, by means of the transmission of power by wire ropes, we may utilize all this power that is now being wasted, and devote it to a useful purpose.

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